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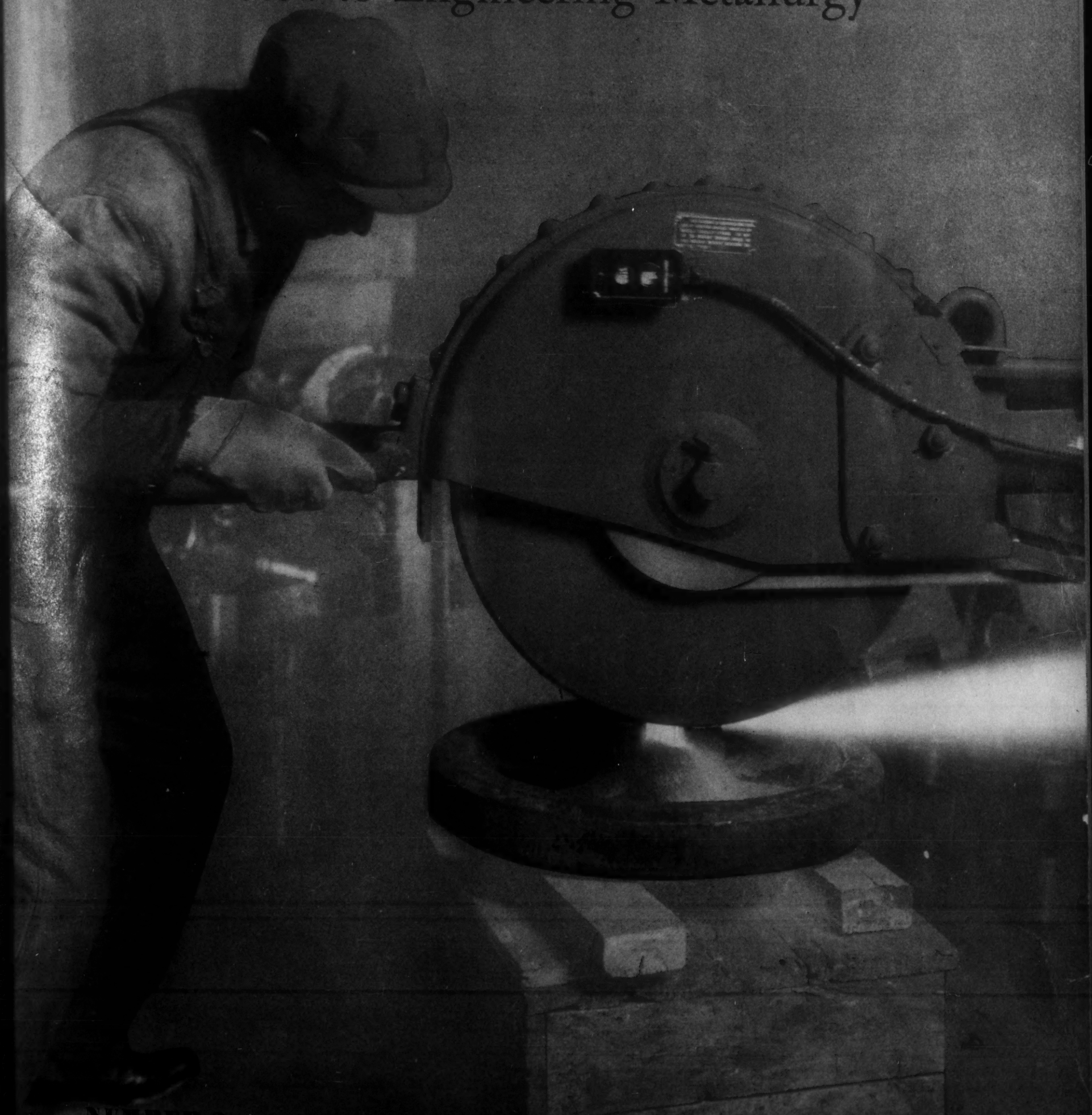

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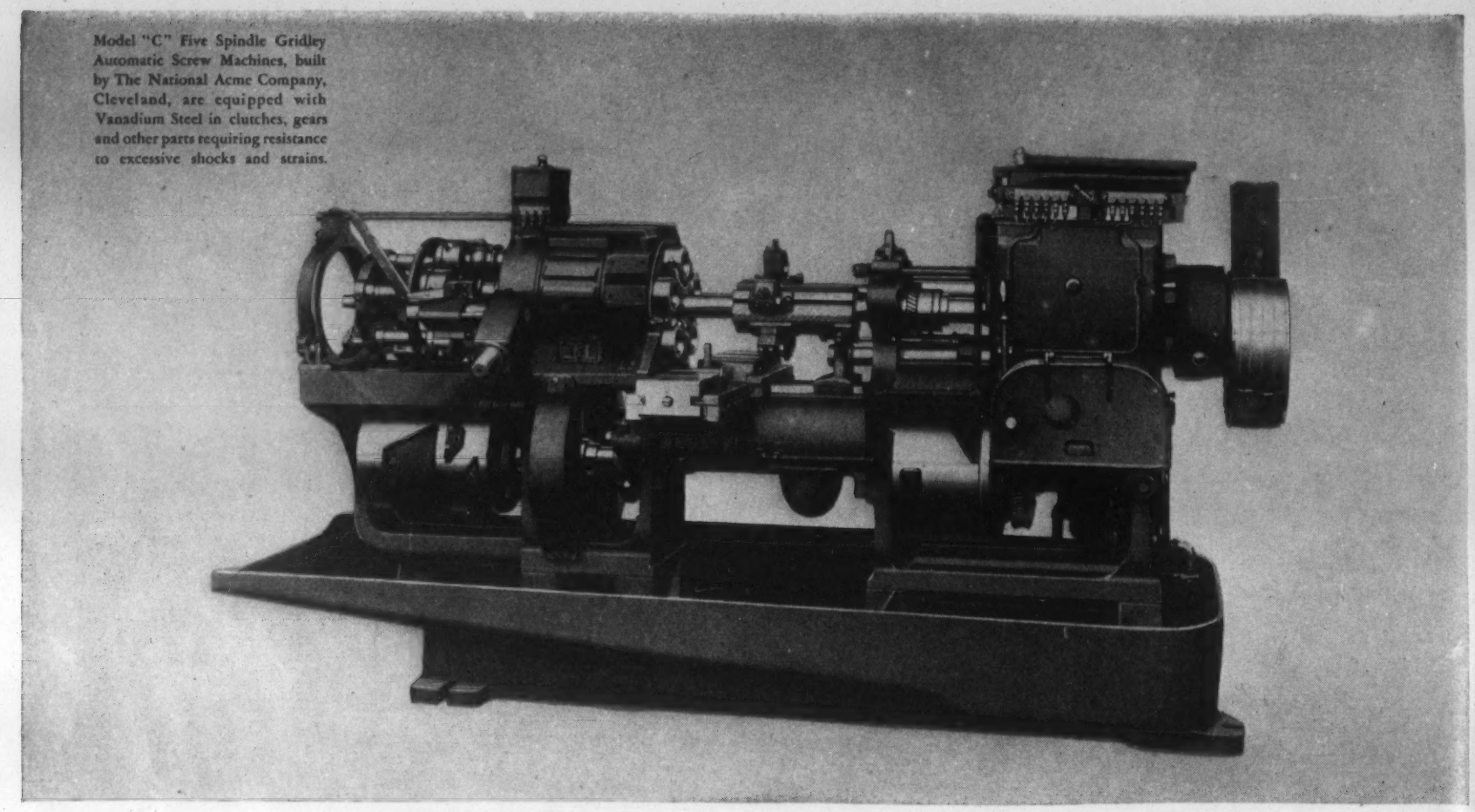

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EDITORIAL COMMENT

The Removal of Metal

INDUSTRY is interested in the removal of metal, and from two quite different points of view. Almost no piece of metal finds its ultimate use without undergoing some sort of machining operation. In many uses of metal parts, their useful life depends on how long they can maintain their original size. Questions of machinability and wear-resistance are of great engineering and economic importance. They enter into the first cost, and the final cost per unit of service, of a large proportion of the things we make out of metals.

Yet the properties of metals and alloys—machinability and wear-resistance—which influence those costs, are vaguely defined, and only approximately measured.

The engineer can design a structure or a machine on the basis of tensile strength and yield point, or even of endurance properties and impact strength, with fair assurance that a measurement can be made in the laboratory that will tell him quite directly what he may expect in service.

In regard to machinability, however, an alloy is described as "easily machinable," "difficultly machinable," or "unmachinable." We have no accepted or acceptable yardstick for machinability.

Wear-resistance is in an even worse state. Who will supply a metal part subject to wear, with a guarantee as to what its life will be, or if he has the temerity to do so, on what quantitative information can he base that guarantee?

Why is it that these admittedly important properties are so nebulous?

We can probably understand both problems better if we take them together as parts of the broad question of the removal of metal, intentionally by machining, unintentionally by wear. The metallurgist may well consider them together since he has often to deal with the selection of an alloy which may be cheaply machined, but which will then keep its form against the ravages of wear. He is between the devil and the deep sea, since the two requirements are obviously antagonistic, and he cannot meet either requirement fully without sacrificing something on the other.

To remove metal, we must first get hold of it, and then tear it off. In order to get a grip on it, in machining or in wear, it must be penetrated, or some promontory on its surface must be engaged with another promontory on another surface. Naturally, the harder the metal, the more difficult it is to penetrate or dent it so as to get a grip. Hardness will then work against machinability and for wear-resistance. But if we use a tool or an abrasive which is itself sufficiently harder than the metal, and use it under enough pressure, we can get penetration and gripping. Resistance to penetration then, is a relative matter, and not an absolute one. Once gripping is accomplished, the difficulty of machining or abrading depends on that combination of properties that resists tearing, which we lump under the vague word, "toughness."

If the abrading tool or particle is itself brittle, we may destroy it before we remove much metal, and the resistance to removal is again a relative matter, depending on the properties of the co-acting materials and the forces applied.

It is this dependence upon external circumstances that makes the problem so difficult to deal with. We can machine materials that were unmachinable with ordinary tools if we use a tool of suitable hardness and toughness. Thus high speed steel with its property of red hardness, tungsten carbide tools, and abrasive wheels for precision grinding, have all made it possible to machine materials so hard, so tough, or so hard and tough that they could not be handled otherwise. But in grinding the hard, tough steels we do not necessarily use the hardest abrasives, such as silicon carbide, but rather those of lesser hardness but greater toughness, such as fused alumina.

If we have two co-acting metal surfaces, one hard and one soft, with an abrasive between, we often find that the softer one acts as a lap, picks up the abrasive and wears away the harder surface with it, instead of wearing away itself. In the case of true metal to metal wear, without other abrasive, we cut down wear if we start with initially smooth surfaces, so as to cut down gripping, or if we have a film of lubricant that actually prevents metal to metal contact. If we cut down the relative slip, as by substituting rolling for sliding friction, letting the wheels run on the track instead of putting on the brakes, that, of course, reduces wear.

Some of the factors involved are easy to visualize and understand. Others are not so clear. Why should hard rubber and bakelite, so easy to whittle, be so ruinous to metal-working tools? Why should a silk fish-line wear away the agate guides?

Why is there such a vast difference in the machinability of metals in turning and in drilling? Why do metals stand in one order for wet-grinding of an abrasive material, and in quite another for dry grinding?

In many services resistance to pure abrasion of the surface is only one factor. For that alone we might find the optimum in a hard material with some, but not very much, toughness, but where impact also is involved, as in ball-mill balls or in tire chains, we need toughness in the body of the metal as well as on the surface.

That careful machinability tests will tell much about the relative ease of cutting of two alloys, but that so many variables are concerned that sweeping predictions from a single test are out of order, is clearly brought out by Professor Boston's recent work on

(*Continued on Page 38*)

To Our » » Subscribers

The February issue of METALS & ALLOYS is the last that you will receive until September. We are already working on a special issue to be ready in time for the "Metal Show" in September.

Your subscription will be extended six months to compensate for your not receiving the paper during the next six months. Meanwhile the abstract service will be continued and mailed to you monthly as a bulletin, without extra charge.

On the opposite page we take you into our confidence and explain fully the reasons back of this somewhat unusual move.

A few years ago Henry Ford withdrew Model "T" from the market, and closed his plants to re-equip for production of the new Model "A". When we resume publication in September, we will give to the metallurgical public a much improved METALS & ALLOYS.

We are shutting down for six months to accomplish four definite objects:

1st—We will avoid the publication of six issues which could only be produced at a heavy loss. Since we commenced publication twenty months ago we have incurred a deficit of over forty thousand dollars. To put the paper on a self-supporting basis we must carry a heavier volume of advertising.

2nd—We will work to increase our circulation by at least two thousand beyond our present four thousand.

3rd—Our advertising staff will work to secure additional advertising contracts to begin with September.

4th—Our editorial department will arrange for a program of added features which, without impairing the usefulness of METALS & ALLOYS to our present subscribers, will broaden its appeal.

We ask and confidently expect the co-operation of every reader of METALS & ALLOYS in accomplishing these objectives.

cold-drawn steels, abstracted on page 44 of the abstract section of this issue.

As soon as we start to think fundamentally on these subjects, we can see that so many variables are brought in by the conditions of service—quite outside of the alloy itself—to determine the usefulness of the alloy in that service, that it is hopeless to expect to find a single figure to express what the machinability or wear resistance is, except in particular relation to the conditions of service.

Hence, Herbert[1] expresses the situation by saying, "Machinability is not to be regarded as an attribute of a metal, but of a metal *and* a machining process." This can equally well be paraphrased to apply to wear-resistance. Boegehold[2] has stated that the design of a universal wear-testing machine is in the same category as that of a perpetual-motion machine. In both problems, we must "make the punishment fit the crime," and select our test conditions to correspond with those of service. The test methods should be tailor-made, not ready-made. In no field of testing is extrapolation beyond the actual conditions of test less safe. Indeed, much of the confusion in respect to machinability and wear-resisting properties is due to investigators trying to draw general conclusions from a limited series of tests.

How then can we get to the point where we can satisfactorily evaluate these properties in a quantitative fashion? Obviously only by the slow and laborious process of developing different methods of test for the study of extremely specific problems, and seeing how the results agree with practice. We are in the situation of the youngster with his arithmetic, who has to do some sums and look in the back of the book to see if he did them in the right way. If he did, he can proceed to solve the problems, for which no answers are given, with some assurance that the results are correct. If we can work out tests for machinability or wear resistance that will place in the right order a series of alloys which vary in those properties in a fashion known by accumulated practical experience, then we can proceed to study the properties of new alloys with some hope of correctness. If we can bring such a determination into the laboratory where test conditions can be rigidly maintained, then we can operate more rapidly and cheaply than by relying on observations of performance in service.

Where methods of test in the field of removal of metals have been chosen to correspond rigidly with service conditions, useful results have been obtained, but we are still a long way from the point where technical society committees can effectively approach standardization of test methods. Fortunately, the committees dealing with machining and machinability are research committees rather than standardization committees. No committees on wear of metals appear to have been established so far. Indeed, it is a question whether such a committee could accomplish much as yet.

What we need most just now is to have published accounts of attempts at such testing, whether successful or unsuccessful. We can learn as much in regard to the engineering application of various sorts of tests from our failures as from our successes.

There are few types of testing machines on the market for the study of the removal of metal, and none that is universally accepted. There has however been a great deal of work in this field, especially in regard to wear, but it has not gotten to the point where the investigators are sufficiently satisfied with the results to publish them.

Articles in this issue describe some useful and illuminating work in these fields, and we hope that other authors will overcome their diffidence and recount their own experiences, even though they may be limited. We need many more pieces before the whole picture-puzzle can be fitted together.—H. W. G.

[1] E. G. Herbert. The Problem of Machinability Measurement. *Metallurgia*, Vol. 2, Sept. 1930, page 169.
[2] A. L. Boegehold. Wear Testing of Cast Iron. *Proceedings American Society Testing Materials*, Vol. 29, II (1929) page 115.

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An Unhonored Genius

A considerable group of presumably highly intelligent persons has just decided that Josiah Willard Gibbs was not sufficiently great to justify his inclusion in our so called Hall of Fame.

In this day when it is fashionable to render lip service to the cause of research and when relativity is supposed an interesting subject of social chatter the name of the most profound scientific thinker of our nation is so far unknown to some hundred representative intellectuals as not to command the necessary majority. The inconspicuous Yale professor's achievements equaled those of Faraday and rivaled those of the illustrious Newton. His work on Heterogeneous Equilibria is the foundation of half a dozen European reputations in physical chemistry and the chief corner-stone of scientific metallurgy.

If this man be unworthy of enduring fame, what service must an American render humanity to be remembered? Does the fault lie in this particular jury's ignorance of Gibbs' achievements or in an utter lack of perspective as to science, the arts, statesmanship and war. Amiable but mediocre rhymsters and successful butchers of humanity have in the past found place where a scientific master builder is excluded. Gibbs' work was substantially unappreciated in his life time; perhaps it is but natural that his name should not survive his death but what a commentary upon American civilization that it should so little appreciate its greatest scientific genius.—H. A. S.

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The Making of Physical Metallurgists

One of our Editorial Advisory Board is concerned as to the quantity and quality of the metallographers or physical metallurgists of the future, for he has suggested as suitable subjects for discussion in METALS & ALLOYS, the number of students taking metallography and the necessity for more than the regulation four-year course in order to produce competent metallographers.

The term "metallographer" never did appeal to us very much, for it tends to convey the idea of a man who prepares specimens, and uses a metallographic

(*Continued on Page 50*)

GRINDING

of Metals and of Refractories

By H. W. Wagner[1]

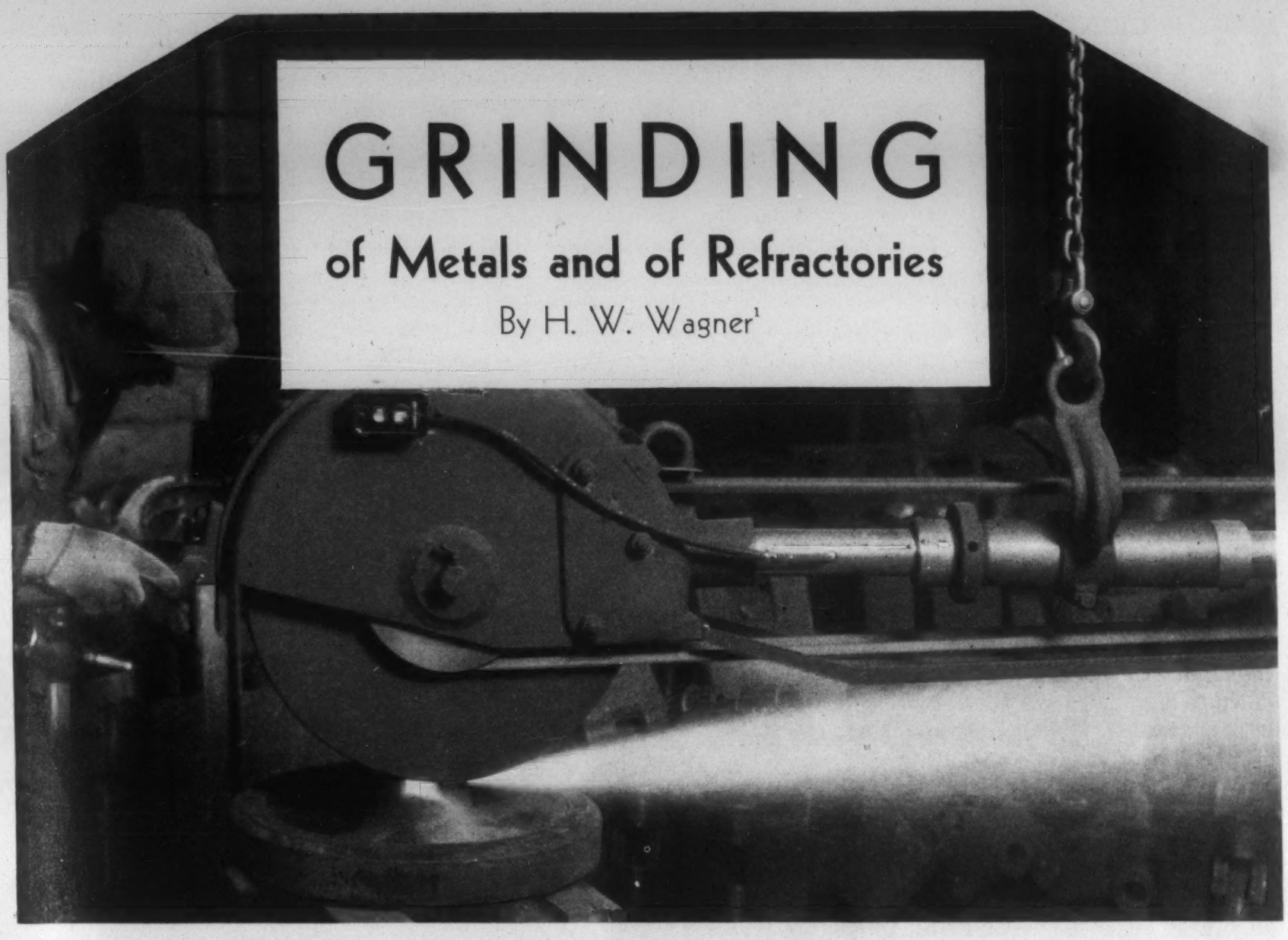


Fig. 1.—Modern Type of Swing-Frame Machine, Grinding a Steel Casting with Bakelite Wheel Running at High Speed

FROM the viewpoint of manufacture, metals and refractories are two classes of materials related one to the other. From the grinding viewpoint, the two classes afford contrasts and comparisons both interesting and illuminating. For one thing, with metals, quantities involved and accuracy demanded in grinding rather overshadow similar factors for refractories. Most instructive, however, is the effect of intrinsic properties upon choice of abrasive.

CHOICE OF ABRASIVES

Metals and refractories—these materials are differentiated from each other by their physical properties and by their behavior when machined. Toughness is imparted to metals by strength and by a second property. This second property is the amount of flexure or other distortion of the body up to rupture. Refractories, on the other hand, are brittle, being unable to flex to any considerable degree without fracturing.

Metals, in their soft or annealed condition, can be worked readily with a steel tool, whereas refractories always dull a steel tool rapidly when it is used on them. In grinding, these essential differences are apparent by the type of abrasive found most suitable.

On metals, aluminous abrasive (fused alumina) is most commonly used; on refractories, silicon carbide. Why? Because aluminous abrasive is tougher than silicon carbide, and because silicon carbide is harder than the fused alumina. Getting down to specific cases, consider a steel casting and a hard refractory brick. Each is to be snagged or rough ground to remove irregularities.

The steel casting has strength and ductility, and because of these properties a comparatively large amount of energy is required to tear chips from it. This resistance is matched by the toughness of fused alumina, while the more brittle, although harder, silicon carbide would be broken and shattered, resulting in poor grinding economy. The refractory brick is harder than the steel but because of its brittleness requires less energy than the steel did to be torn apart. Therefore, silicon carbide will grind it without undue destruction of abrasive, and is hard enough to properly maintain sharp cutting points. Fused alumina would be dulled comparatively fast by the refractory, so that an excessive rate of wear would be necessary to expose fresh, sharp grains rapidly enough to maintain a satisfactory rate of cutting.

PRODUCERS and users of metallic products realize the value of modern grinding methods both in the extreme precision of dimensions attainable, and in the ability to form parts from unmachinable alloys. But relatively few users of refractories realize that the bricks of a furnace lining, for example, can be shaped by grinding instead of by a chipping hammer. When the brick mason learns to use refractories that are accurately trued up to fit instead of relying on thick layers of cement to make up for the inaccuracies, we may expect better refractory life. This article should be of interest not only for its intrinsic information but by suggesting useful applications of grinding furnace refractories.

[1] Research Laboratories, Norton Co., Worcester, Mass.

GRINDING REQUIREMENTS

There are five basic requirements to be considered when judging the success of a grinding operation:

1. Rate of removing stock.
2. Life of grinding wheel.
3. Finish left by grinding.
4. Accuracy of finished pieces.
5. Escape of injury to work by softening, cracking, etc.

The first two requirements are important on all production jobs. Each of the others may or may not be important on a given job.

Rate of removing stock counts heavily by virtue of its influence on labor and overhead cost per unit ground. It is dependent upon speed of grinding wheel, wheel size, nature of wheel structure, and suitability of machine. Grade of wheel (strength of bonding) must be soft enough so that dulled cutting grains are torn from the wheel. Otherwise, it will not cut freely and fast enough. There is an optimum grain size for fast cutting, usually ranging from size 10 to 60, depending on material and set-up.

If the grade of wheel is too soft, wheel life will be too short and wheel cost per unit ground will become too high. Choice of wheel specifications often narrows down to a grade which will provide economical balance between rate of cutting and rate of wheel wear.

When finish is a factor, choice of wheel must be such as to provide an economical balance between rate of cutting and finish. This is because the smoothest finish requires a grain size finer than that which cuts fastest. Finish also requires a slightly dulled wheel which does not cut as freely as a sharper wheel. Ordinary metallic bearing surfaces generally call for a "commercial" finish. Both ordinary roughing and commercial finishing often are done by the same wheel by means of skillful truing and manipulation, to fit each operation in turn.

Accuracy is largely a matter of machine design, condition and operation. The cutting action of the wheel must, of course, be free and true, with little distortion of the work through heat or excessive pressure.

Materials most subject to injury by grinding are sensitive hardened steels, tungsten carbide tool metals, and brittle non-metallic materials including some refractories. Excessive heat generated by grinding may draw the temper of a hardened steel. Any of the materials mentioned may be checked or cracked by excessive heat generated from improper grinding.

To minimize danger of injury by heat, the optimum grain size needs to be chosen, feed should not be forced, and glazing (excessive dulling) of the wheel face should be guarded against by using a soft grade of wheel and by frequent dressing if necessary. Aluminous abrasive grain 46, grade H, and vitrified bond are specifications for a typical wheel for surface grinding sensitive steels.

CLASSIFICATION OF MATERIALS

A comprehensive and logical classification of materials with reference to their behavior when ground is next to impossible. However, a rough partial list is presented:

A. METALS
   1. Soft non-ferrous metals, as aluminum, copper, lead, etc.
   2. Ductile steels and irons, carbon and alloy.
   3. Non-ductile irons.
   4. Hardened steels, carbon and alloy.
   5. Hard non-ferrous metals, including tungsten carbide tool metals.

B. NON-METALS
   1. Comparatively soft materials,

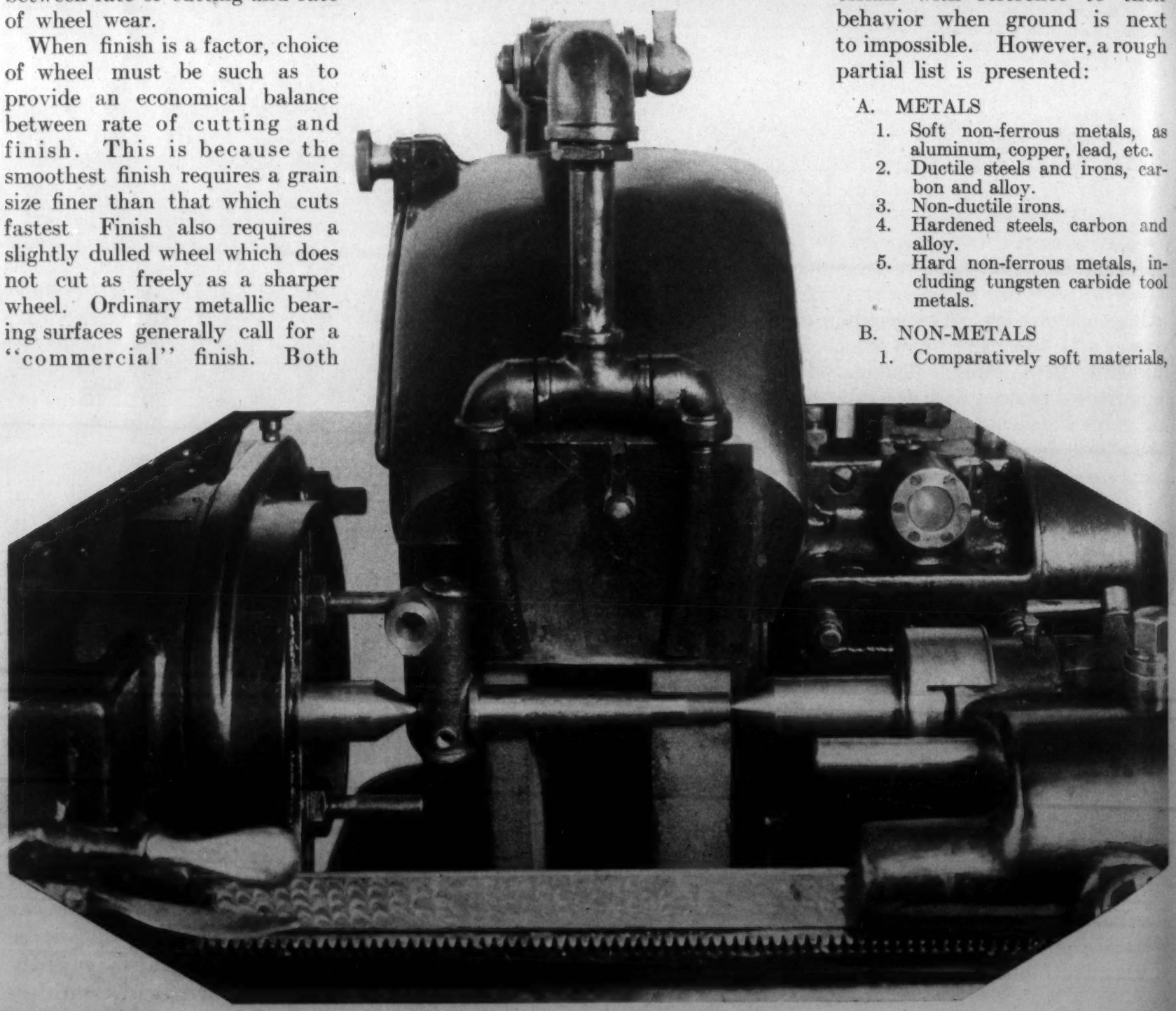


Fig. 2.—Twin Wheel Mounting. By Grinding Two Diameters in One Operation the Cost of Parts Made in Large Quantities Is Reduced

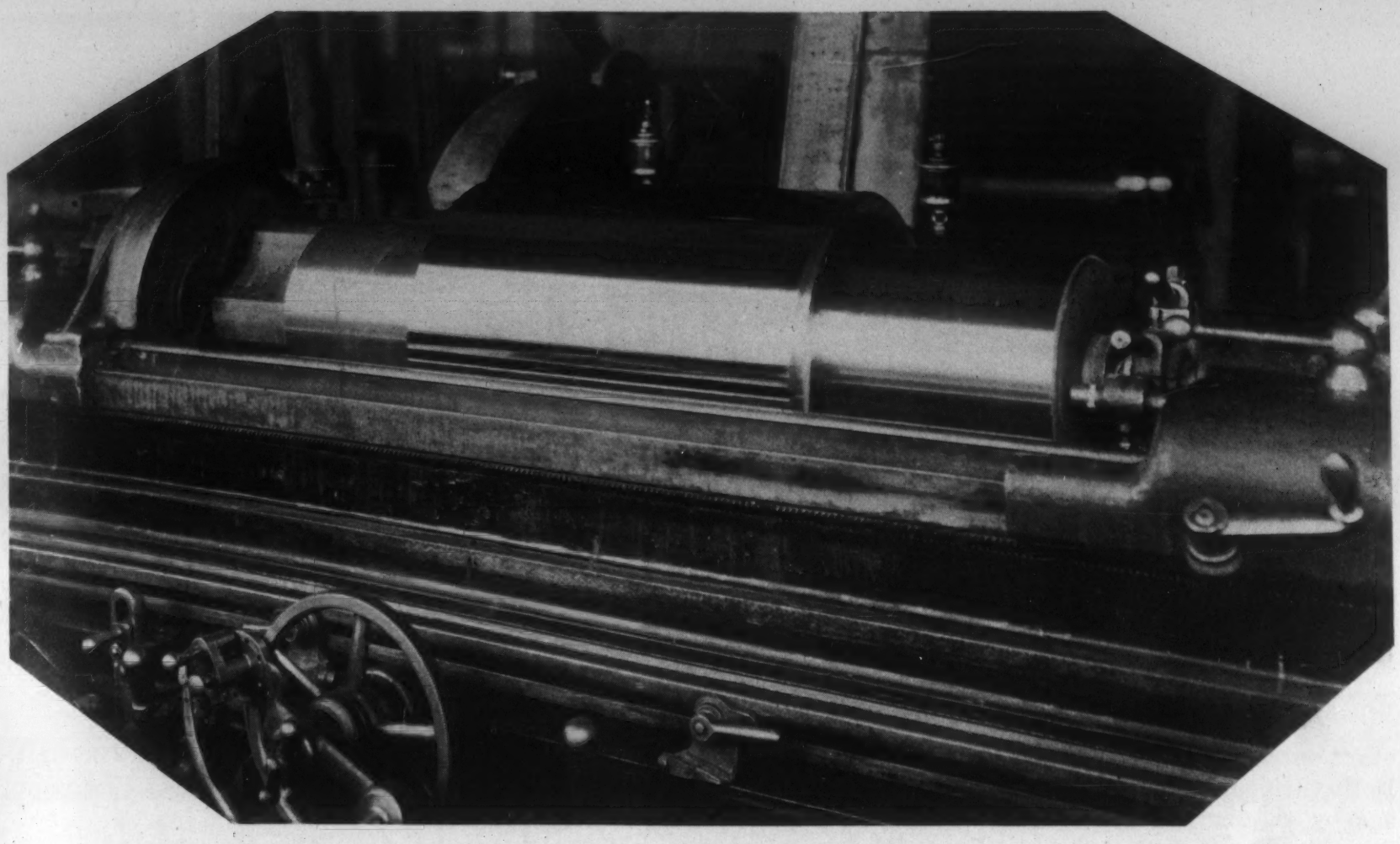


Fig. 3.—Roll with Mirror Finish Created by Grinding. The Same Type of Finish Is Produced on Both Chilled Iron and Hardened Steel Rolls with a Fine Grain Silicon Carbide Shellac Wheel

including natural and artificial woods, bones, shells, fiber products, synthetic resins and related products.

2. Hard materials, including refractories, other ceramic ware, natural and artificial rocks, etc.

From the list just presented, it is apparent that refractories are responsible for very little grinding, as compared with metals. In fact, the ductile steels and irons division of metals accounts for more grinding than is done on all non-metals. To help out the smaller end of our subject, then, later grinding discussion will include all hard non-metals with refractories because they all have certain types of properties in common.

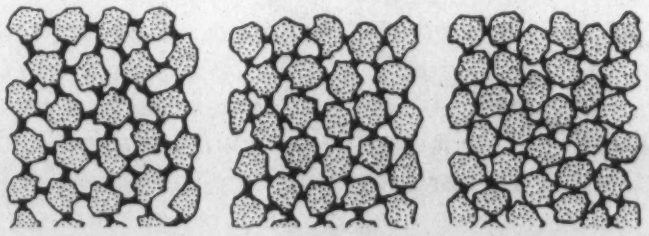


Fig. 4.—Abrasive Grain Spacing in Grinding Wheels, as Illustrated by Diagrammatic Sketches. Relative to One Another They Represent Open (Left), Medium (Middle), and Close (Right) Spacing of Grains. All Can Be Manufactured to Have the Same Grade or Resistance to Wheel Wear. Yet Each Structure Has Its Own Advantageous Application

FUNDAMENTAL SPECIFICATIONS

Selection of abrasive is the first step toward successful grinding. With a given material and form of work piece, and with required rate of production and degree of finish and of accuracy known, items to be specified include:

WHEEL
- Kind of abrasive
- Grain size
- Grade (strength of bonding)
- Average spacing of abrasive grains
- Kind of bond
- Size
- Part used (periphery or side)

CONDITIONS
- Speeds of wheel and of work
- Wet or dry grinding
- Method of dressing the wheel
- Type of machine

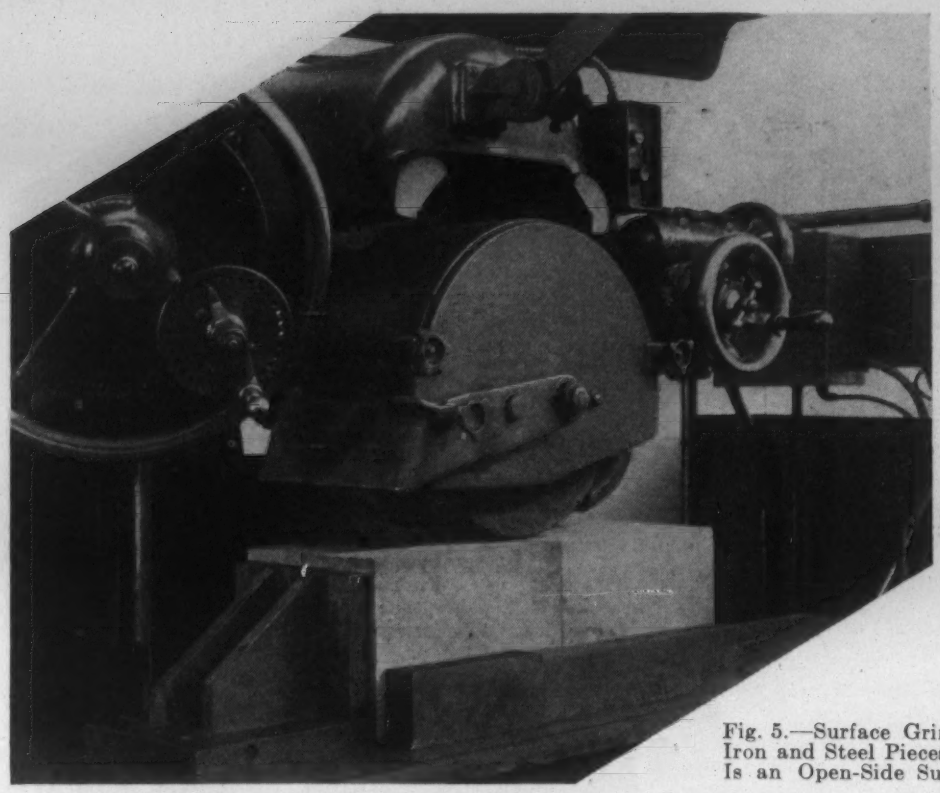
Full description of grinding wheels and discussion of conditions are too lengthy to be undertaken here. It might be pointed out that grade (strength of bonding) of wheel has no reference to hardness of, nor to any other property of the abrasive. It is true, however, that for the same grade letter a finer grain size of wheel is stronger and more resistant to wear. This statement applies particularly to vitrified wheels and to grain sizes 100 and coarser. Referring to grain and grade, a higher number means a finer grain size: a later letter from the alphabet means a harder grade.

GRINDING OF METALS

Grinding of metals is actually a book-long subject. Abrasives already have been discussed. Special applications of silicon carbide will be described later. Other fundamentals listed in the preceding section will be touched on very briefly.

Coarse grain sizes are generally used for fast cutting and reduction of loading. Fine grain sizes are employed for fine finish, and on some hard steels not easily penetrated.

Grinding wheels made with vitrified bonds are most universal and are most stable chemically and thermally. They have a clean, crisp cutting action. Silicate bonded wheels are used when very soft wheel action is desired, and on cutlery grinding and on some



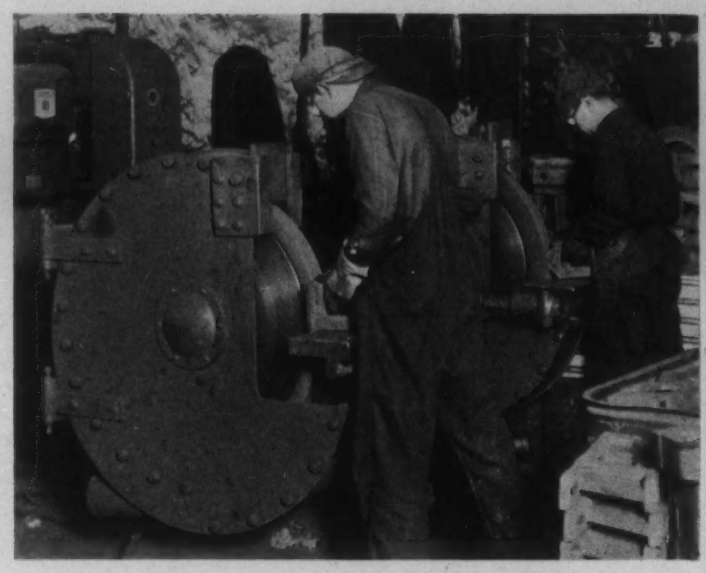


Fig. 6.—Double-End Floorstand with Segmental Vitrified Wheels Designed to Run at High Speed

Fig. 5.—Surface Grinding Set-Up of Refractory Blocks on a Magnetic Chuck. Iron and Steel Pieces Around the Blocks Hold Them in Place. The Machine Is an Open-Side Surface Grinder Equipped with Hydraulic Table Traverse

other operations formerly done by natural sandstones. Both vitrified and silicate wheels are subject to breakage by differential expansion when heated by severe dry grinding without artificial cooling. Recommended operating speeds generally do not exceed 6500 feet per minute at the periphery.

Wheels made with organic (shellac, rubber, Bakelite) bonds do not break from heat of grinding, but the bond at the working surface can be weakened by heat, leading to secondary wheel wear. These bonds are suitable for thin wheels which must be somewhat flexible. They impart sufficient strength to abrasive bodies so that wheels may be run at speeds exceeding 6500 feet per minute without danger of breakage by centrifugal force. These bonds also have a polishing function on some jobs.

Grade of wheel (strength of bonding) is chosen to match severity of operation so that the wheel wears just enough to remain reasonably sharp.

Average spacing of abrasive grains in the grinding wheel lately has become recognized as important when fitting the wheel to the job. Wheels of different grain spacing, but having the same grade or rate of wheel wear, may have quite different grinding actions on a given job. One of the latest developments in the manufacture of grinding wheels is control of average spacing of abrasive, using just enough bond to provide the desired grade. Product of the new development is called "controlled structure."

For moderate or average operations, wheels are made with a medium spacing of abrasive. For very severe operations as heavy snagging or in cases where the corner or other portion of the wheel is in danger of losing its shape, the tendency is to use a closer spacing of abrasive. For very soft grades, in which percentage of bond must be low, a wheel is felt to be more stable and versatile, and therefore more successful if made with comparatively open spacing of grains.

Size of wheel, practically, is determined by the machine. The modern tendency is to go to larger wheels to improve economy.

The periphery of a wheel acts softer and cuts more freely than does the side. The side leaves a smoother finish on the work.

Most wheel speeds are within the range of 4000 to 10,000 feet per minute at the periphery. In general, the higher the wheel speed, the faster is the practical rate of cutting. Conditions and requirements in some cases prevent full advantage being taken of a higher speed. For one thing, there is more danger of burning the work with a higher wheel speed. Maximum speed is limited also by strength of wheel body, which must resist breakage by centrifugal force. For a given set of conditions where the work has a regular motion, there is an optimum work speed which gives best results. Optimum work speed is determined by trial rather than by prediction.

Dry grinding requires less elaborate equipment than does wet grinding which is sloppy unless the machine is properly designed. Wet grinding reduces distortion and danger of burning the work, improves final accuracy and reduces loading. Water tends to make the wheel act softer.

Dressing of the grinding wheel is done to true the wheel and to control sharpness of abrasive, or finish produced on the work.

Type of machine, naturally, is determined by character of the grinding operation. Ample power, rigidity, durability, accuracy, versatility and guarding of the wheel are essentials of a successful grinding machine.

One bugbear in the way of meeting several requirements is loading. Loading means that particles of the work being ground stick to the working face of the grinding wheel. It is most likely to occur with soft, ductile or sticky materials. The particles of load clog the pores of the wheel, get in the way of abrasive cutting points and scratch the finish on the ground work.

Remedies which reduce loading are: wet grinding, use of a coarser grain wheel, and special treatments or fillers with which pores of the wheel are impregnated.

As pointed out earlier, aluminous abrasives are gen-

Fig. 7.—Production Axe Grinding. Tapered Steel Mounting Flanges Fit on Tapered Wheels to Hold the Pieces in Case of Wheel Breakage

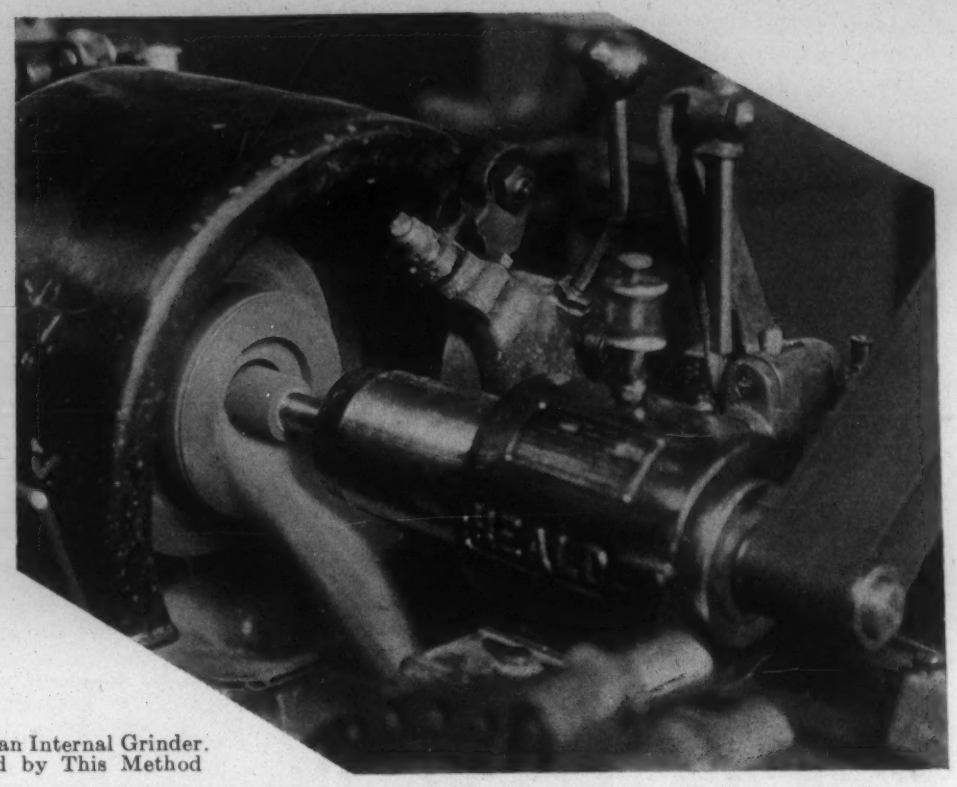


Fig. 8.—Grinding the Hole in a Work Piece with an Internal Grinder. Close Accuracy and Fine Finish Are Attained by This Method

erally used on metals. There are several exceptions, however, in which silicon carbide is used for various reasons. Five are pointed out:

1. Grinding cast irons, where resistance of the material and when severity of operation are not great enough to shatter silicon carbide grains rapidly. In this case the greater hardness of the silicon carbide can be utilized to advantage.
2. Grinding hardened steel and chilled iron to a mirror finish. A popular wheel is silicon carbide, grain size 500, grade I, shellac bond.
3. Cylindrical grinding of some chromium steels. Fused alumina seems to have a peening action in some cases, which trouble is overcome by the greater intrinsic sharpness possessed by silicon carbide. Fused alumina has a tendency to ride the work or, if the wheel grade is soft enough, the wheel face suddenly gives way, resulting in excessive wear. Grain sizes are 46 to 60, grades K to O.
4. Grinding of tungsten carbide tool metals. This is plainly a case of the work being too hard for the aluminous abrasive, so the harder silicon carbide is needed. Grain sizes range from 60 to 220, grades G to J, and even harder on some operations.
5. Grinding very soft or "sticky" metals which load the wheel. On many such substances the intrinsic hardness and sharpness of silicon carbide promote cleaner cutting and less smearing.

GRINDING REFRACTORIES

Many of the general principles which apply to the grinding of metals apply to that operation on refractories also. Refractories and similar materials differ from metals in that:

1. They are less likely to cause loading of the wheel because of their brittle nature.
2. Precision operations are more rare, relative to rough surfacing and sawing or coping.
3. Injury by grinding is more likely to be flaking of surface or chipping of edges.

Rough surfacing is meant to include removal of high spots, general smoothing and reduction of dimensions, to make the piece fit in position. Such work is done on furnace bricks and other shapes, glass tank blocks, porous plates for sewage and chemical tanks, terra cotta shapes, sanitary ware and floor and wall tile.

Tile are trimmed for fitting and bricks are cut up into sample blocks by cutting-off wheels as thin as $^3/_{32}$". A typical wheel specification for the more resistant bricks is silicon carbide, 24 grain, grade R Bakelite bond. A typical grain and grade for soft tile is 46-N, Bakelite bond. For coping marble and granite, somewhat larger wheels are used, with grains 20 to 36 and grades N to R.

Refractories and other hard non-metals offer a large range of resistance to grinding. Fireclay bricks are surfaced or sawed almost as easily as the proverbial cheese. A dense silicon carbide furnace brick is extremely resistant, because its body consists of one of the hardest commercial abrasives, strongly bonded together. Cost of working such a brick is high in both labor and wheel expense. Marble and granite also offer a contrast in grinding resistance.

For freehand smoothing or machine surfacing of refractories, a typical wheel would be made of silicon carbide, vitrified bond, 36 grain size, grade L. If the wheel dulled too rapidly, a softer grade would be prescribed. Conversely, a harder grade would remedy excessive wheel wear. For some heavy jobs like swing frame grinding of very hard glass tank blocks, a coarser grain, as size 16, and a harder grade, as T, are suitable. For light hand operations, fastest cutting of very hard non-metals is often reached with grain size about 60.

Just as some silicon carbide is used on metals, so is some aluminous abrasive used on materials in the hard non-metal class. For instance, a fused alumina 220 grain, grade M, vitrified wheel is recommended for edging glass lenses. Finish explains this particular excepton. The aluminous abrasive dulls or glazes and, although cutting slowly, imparts a smooth edge to the lens. Silicon carbide cannot be properly dulled by the glass and so persists in scratching.

In one plant, silicon carbide was replaced by aluminous abrasive after it was found that silicon carbide left an objectionable chemical contamination while grinding glass tank blocks.

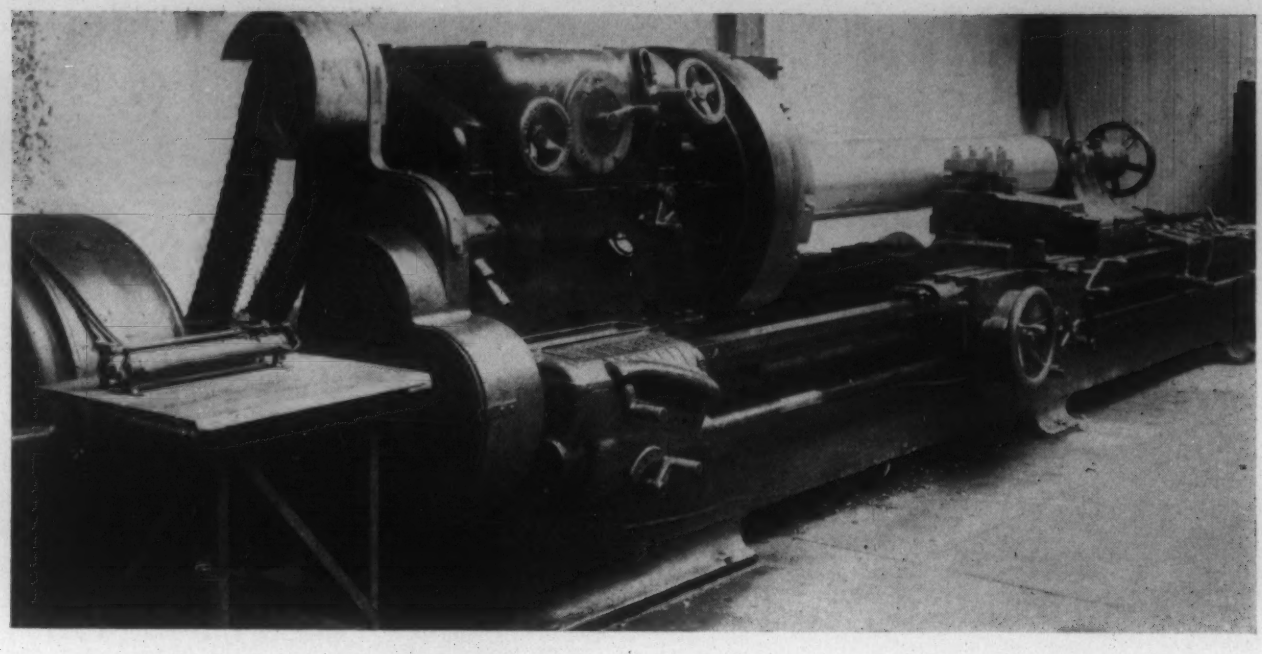


Fig. 1.—Equipment Used at the Bureau of Standards for Break Down Test of Lathe Tools

Machinability and Tool Life*

By T. G. Digges**

THE discovery of high speed tool steel about 1900 by Taylor and White was one of the outstanding contributions to the field of metallurgy. It opened up a new era in machine shop practice and made possible an increase in production beyond the fondest dreams of the production engineers. It was in a large measure responsible for those developments which have given us present-day methods of mass production.

In recent years, many investigations have been carried out in America, England and Germany in developing and testing tool steels and studying the machining properties of metals. While these researches have given data of inestimable value, much of the information they have produced is not in a handy form for the engineer's use. Therefore, it is the object of this article to give a general discussion of the subject that will be of practical use to an engineer interested in tool selection and machining problems. An attempt will be made to appraise some of the best known test methods for tool comparisons and the determination of machinability.

The various criteria used to evaluate machinability have left much confusion in the use of this term. To some, machinability has meant the finish produced on the work piece, to others it expresses the forces on the tool during the cutting operation, or the power required in removing metal, while to still others it has denoted tool life, or the amount of metal removed in a given period of time, etc. Any or all of these factors may be important under certain conditions and may contribute to what has been called machinability.

For example, in rough turning the primary object is to remove the maximum amount of metal in a minimum time at the least cost. Under such conditions the most important factor is tool life and it follows that those materials which, under otherwise fixed conditions, permit the longest cuts without regrinding of the tools may be described as the most readily machinable or to have the highest degree of machinability. Under such conditions the power required and the finish left on the work piece are of secondary importance.

In other cases, the finish may be of major importance and the amount of metal removed, the power required in cutting, the forces on the tool, or tool life may or may not be of special interest.

A clear, concise definition of machinability, satisfactory to all concerned, would set aside much of the existing confusion. It would be difficult to give such a definition and it is not within the scope of this article to enter into such an argument. However, in most cases the limiting condition of machinability is tool failure, and machinability can best be measured in terms of tool life. That is, machinability is proportional to tool life, or conversely to a cutting speed permitting a definite tool life and it is upon this basis that the term is used in the present article.

Machinability tests usually require a relatively long time for completion besides being expensive. For these reasons, many attempts have been made to find some physical property of the materials that can be quickly and easily measured and which permit translation into terms of machinability. This is apparently a hopeless task for such factors as the quality and type of materials being cut, machine tool equipment, cooling conditions, etc., are recognized as factors affecting machinability. However, much useful information has come from such tests and certain physical properties such as hardness values and tensile strength of steels constitute a fair guide to certain machining operations. Thus a steel or material that may be machined easily with roughing cuts may not be equally suited for drilling or threading. Likewise, a tool steel suitable for roughing cuts does not necessarily have the desirable properties for a finishing tool. It is thus not surprising that no physical property of either the tool or the material has been determined that

* Publication approved by the Director of the Bureau of Standards, U. S. Department of Commerce.

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will give an exact criterion of the behavior of the tool or material in the various cutting operations.

Therefore, the test selected to evaluate the quality of a tool or the machinability of a material should primarily depend upon the machining operation to which the tool or material will be subjected in actual practice. In other words, the test conditions should be similar in nature to those in shop practice. In a number of instances tool test methods have been rather extensively developed in the laboratory and it is now possible from the results of such tests to predict with a fair degree of accuracy the behavior of a tool or material for longer time cutting found in shop practice. Some of these test methods will be described and illustrated in more detail in the following sections of this article.

ROUGHING CUTS

Possibly more attention has been given to testing tools for roughing cuts than for any other type of machining. Taylor[1] and his associates after experimenting over a long period of time and making many hundred cutting tests, recommended that a determination be made of the cutting speed producing a tool failure in exactly 20 minutes under otherwise fixed working conditions. That is, this test consists in determining the cutting speed, under fixed conditions of feed, depth of cut, tool angles, cutting material, etc. which will cause the tool to fail in exactly 20 minutes. Taylor, using this method of testing, worked out his well known laws of cutting. Taylor's lathe tests were made in cutting carbon steels representing the type then commercially machined with tools having a chemical composition somewhat different from the high speed tool steels of to-day.

The Taylor test is a satisfactory basis for comparison of both tool performance and machinability of the metal cut. However, it makes necessary the use of more tools, takes more time, requires that more material be cut, and is generally more expensive than the so-called "lathe break down" or life test.

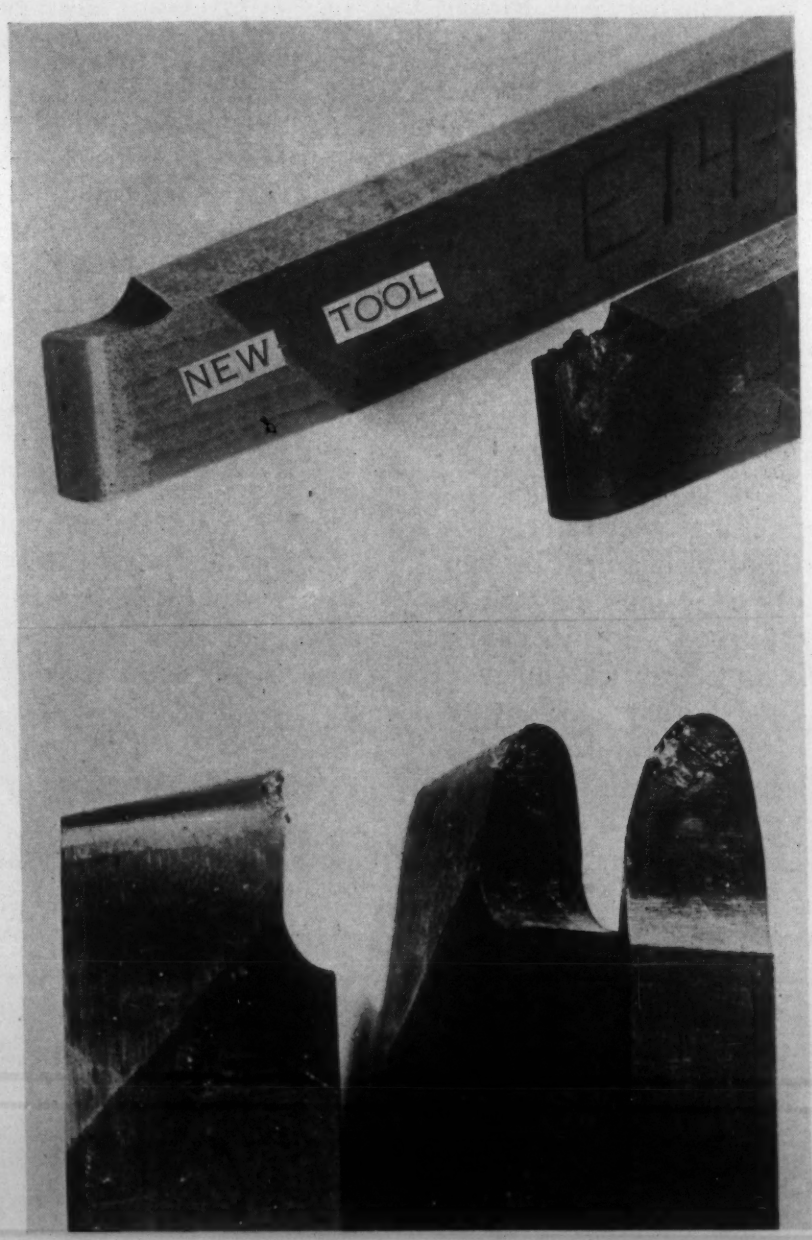

Fig. 2.—Typical Failures of High Speed Steel Lathe Tools in Break Down Test. Note the Wearing Off of the Nose and the Gutter or Groove Worn on the Top Surface of the Tools

In the break down test the tool life is determined under otherwise fixed conditions of speed, feed, depth of cut, tool angles, etc. It differs from the Taylor test in that the basis for comparison is the tool life (time for break down) under fixed cutting speed, while with the Taylor test the cutting speed permitting a 20 minute tool life is the basis for comparison. The results obtained in testing tools in cutting steel forgings with one method of testing may be expressed in terms of the other method by means of computation involving empirical equations.

A heavy duty, motor-driven engine lathe with accurate speed control is best adapted for a comparison of tool performance or a study of machinability in the break down test. No special equipment is required other than a stop watch for recording the time of tool failure. If a record of the power required in cutting is desired, then a voltmeter and an ammeter, or a recording wattmeter, may be used in the armature circuit. It is very essential to have accurate speed control of the work piece, for experiments have shown that a small change in the cutting speed, with a constant feed and depth of cut, has a marked influence on tool life. It is also important that the work piece or test forging be rigid to prevent excessive vibration or chattering of the tool. Care should be taken to have the test forging of a reasonable degree of uniformity in physical properties and to remove an appreciable amount of metal from the surface before making the cutting test. In Fig. 1 is shown the type of equipment that has been satisfactorily used for rough turning tests.

In making comparisons of tool performance from six to eight tools should be tested for each condition and the tests should be made in sequence. Testing tools in sequence has long been practiced and tends to minimize variations in results arising from the inhomogeneities in the metal being cut. For example, in comparing the performance of an 18% tungsten high speed steel tool of a given size, form, heat treatment, etc., with the 14% tungsten type of high speed steel tool of the same size, form, heat treatment, etc., one tool of the 18% tungsten type should be tested, then a tool of the 14% tungsten type tested and then a second tool of the 18% tungsten, then a second tool of the 14% tungsten type, and so on. This procedure should be continued until the desired number of tools are tested and only *average* values should be used for comparison purposes.

[1] F. W. Taylor. On the Art of Cutting Metals. *Transactions, American Society of Mechanical Engineers* (1906).

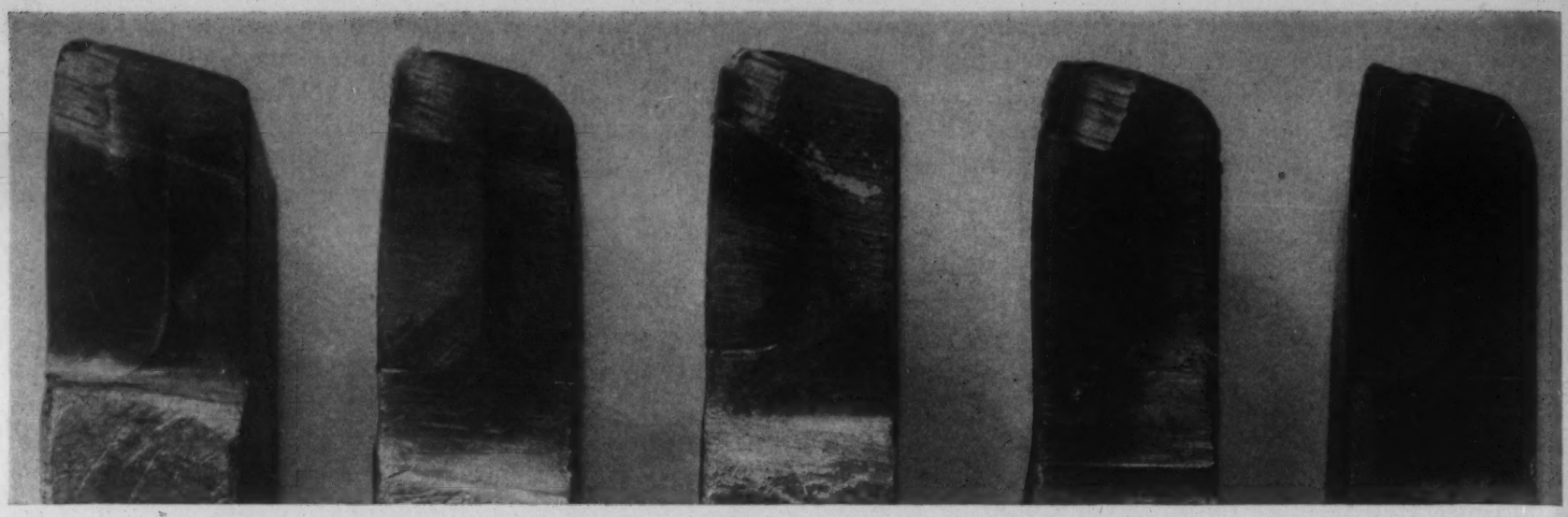

Fig. 3.—Cemented Tungsten Carbide Lathe Tools Used in Break Down Test. All Tools Failed Except Tool Shown on Extreme Left. Note the Depressions Worn on Top Surface of the Tools during Test and the Similarity of Wear to the High Speed Steels Shown in Fig. 2

The cutting tests are usually run "dry" unless a study of the effect of coolants on tool performance is being made. Small tools well supported in a tool holder have given good results and they tend to minimize the amount of material cut. Fairly heavy feeds and depth of cuts should be used and cutting speeds selected to give an average tool life between 10 and 30 minutes.

At the time of failure of high speed steel tools a bright shiny glaze is left on the surface of the test forging so that there can be no doubt in the mind of the operator as to when the end point is reached. Sometimes the tool will continue to cut after the glaze appears but usually the nose will wear off and the tool refuse to cut. The general appearance of high speed steel tools after failure is illustrated in Fig. 2.

The lathe break down test has been extensively used at the Bureau of Standards in studying the effects upon tool performance of both the chemical composition and heat treatment of high speed steel tools and the chemical composition and mechanical properties of the material cut. With this method of test the empirical laws originally worked out by Taylor in rough turning carbon steels have been extended to include the cutting of commercial alloy steels with modern high speed steel tools. More recently the lathe break down test has been extended to include the cemented tungsten carbide tools.

Heavier equipment, capable of operating at higher speeds, is more essential when testing the carbide tools than in the case of tests of high speed steel tools. Since the carbide tools are rather brittle, the elimination of vibration during their testing is also important. The determination of tool failure or end point of the carbide tools is somewhat more difficult than that of the high speed tools. With the tungsten carbide tools, the end point usually results in a glazed surface on the test forging and is often accompanied by a splitting of the chip. In some cases, the end point is often quickly followed by, if not simultaneous with, tool breakage which leaves doubt as to tool failure. The appearance of tested cemented tungsten carbide lathe tools is shown in Figs. 3 and 5.

The lathe break down test has also been adopted by the Navy Department in their specification No. 46S9, July 1, 1926, as the selective test for the purchase of tungsten and certain carbon tool steels. The conditions of this test are somewhat more severe than those usually found in actual shop practice. For this and other reasons, a brand having the highest rating under the break down test does not necessarily show the best tool performance for all the cutting conditions found in the shop. However, the break down test is probably the best criterion that we now have of judging tool performance for it tells part, but not all, of the story.

The lathe break down test has given some valuable information with regard to the machinability of carbon and certain alloy steel forgings. In making such tests it is necessary to have accurate control and knowledge of such factors as the chemical composition, quality of the metal cut, and heat treatment of the forgings after working.

A representative example of results of lathe tests with roughing cuts made at the Bureau of Standards is illustrated in Fig. 4. In this figure are plotted the experimental data showing the relation of the "Taylor Speed" (that is, the cutting speed giving a tool life of 20 minutes) to the tensile strength of the material being machined for a series of tests on a plain carbon and four alloy steels. The data of this figure indicate that if machinability in rough turning is measured by tool life, or by the cutting speed permitting the tools to last a definite time, then measurable and consistent differences may be observed in the machinability of various structural alloy steels. The fact, however, that a given steel permits a higher cutting speed than another steel at some one tensile strength of both materials does not necessarily indicate that the steels maintain a similar relationship at another tensile strength. This is illustrated in Fig. 5, in that for the condition of cutting involved, the 0.3% carbon, $3^1/_2$% nickel steel has the best machinability of the entire group of steels at any selected tensile strength up to about 160,000 or 170,000 lbs./in.^{2} Above a tensile strength of about 170,000 lbs./in.^{2}, the order of superiority is reversed and the chromium-molybdenum and nickel-chromium steels permit higher cutting speed.

Thus the effect of changes in chemical composition of steel forgings upon their cutting speeds is dependent upon the tensile strength at which comparisons are made.

It must be borne in mind that these experimental results were obtained in rough turning with high speed

steel tools of a particular size, form and heat treatment. The order of superiority of the various steels would probably be different if, for example, the tools had been of the new cutting material, cemented tungsten carbide. Cemented tungsten carbide tools are claimed to be especially adapted for cutting alloys having very high tensile strengths but at present there is very little technical information available to substantiate this claim.

FINISH TURNING TEST

Many attempts have been made to find a suitable test for tools when working at relatively high speeds and shallow cuts. Most of these attempts have not given information of industrial value because of the difficulty of maintaining constant cutting conditions. The fact that a tool when taking a finishing turning cut usually shows a gradual wearing away of the cutting edge and does not always fail abruptly, contributes to the difficulty of finding a reliable test method. This wearing away of the nose of the tool causes a decrease in the depth of cut and a corresponding increase in the size of the work piece. With finishing cuts, the adherence to close dimensions is usually required so that the wearing away of the tool is of major importance. This gradual wear of the tool raises the question of what point should be considered as tool failure.

A majority of the investigators studying finishing cuts have made an attempt to measure this wear and have selected some arbitrary point as the end of the test. Both direct and indirect methods of measuring the wear on lathe tools under shallow cuts have been used with varying degrees of success.

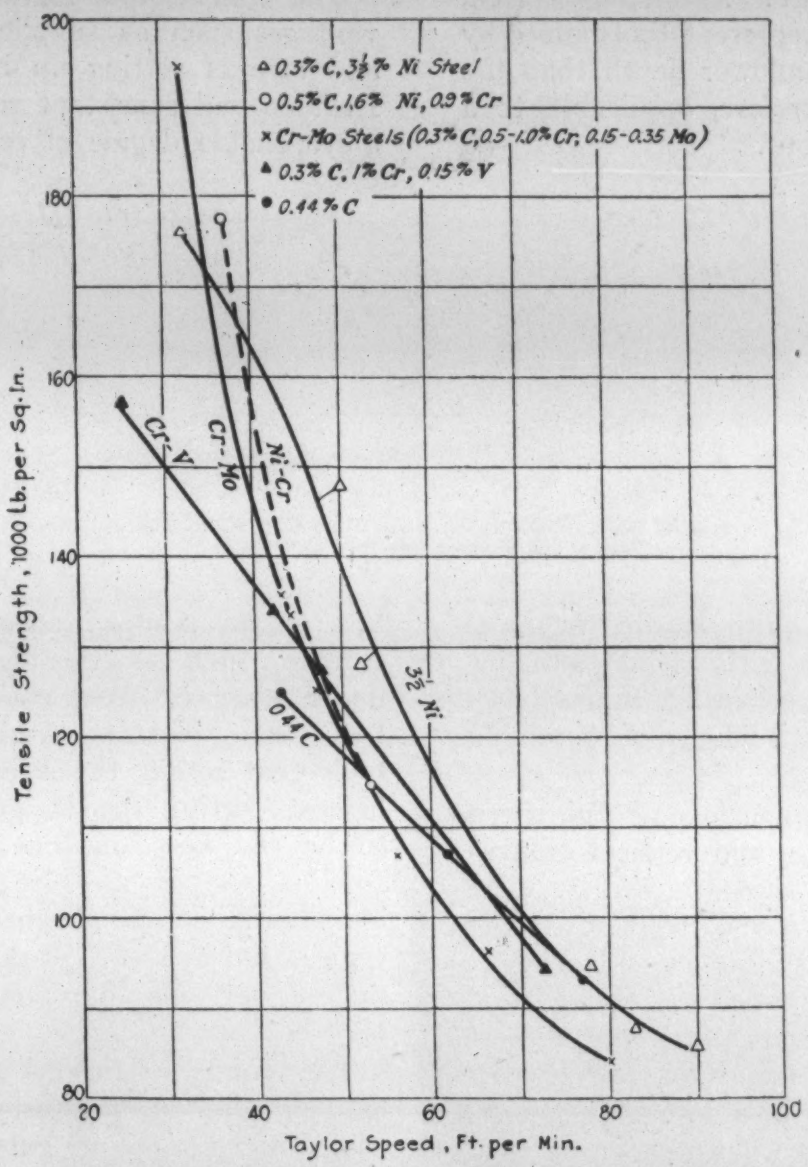

Fig. 4.—Relation of Taylor Speed to Tensile Strength in Rough Turning Heat-Treated Special Steels. The Lathe Tests Were Made with 18% Tungsten High-Speed Steel Tools Quenched from 2400° F. and Tempered at 1100° F. Tools were 1/4 × 1/2 Inch in Cross Section and Ground to a Front and Side Clearance of 6°, Side Slope of 14°, Back Slope of 8° and a Nose Radius of 1/8 Inch. All Tests Were Made in "Dry" Cutting with 3/16 Inch Depth of Cut and a Feed of 0.028 Inch per Revolution.

A direct method of measuring the wear on lathe tools when taking shallow cuts has been worked out at the Bureau of Standards. This method of test is illustrated in Fig. 6. It makes use of two tools set at equal depths in one tool holder, and depends upon the fact that the "trailer" or following tool will not cut so long as the "leader" or cutting tool shows no wear.

A micrometer adjustment is provided in the groove in which the trailer tool is placed in the tool holder. With this arrangement the two tools can be set at equal depths or the trailer tool can be set at a shallower depth if it is desired that greater wear shall represent tool failure. With this method of test the trailing tool indicates when the leader or test tool has worn

Fig. 5.—Cemented Tungsten Carbide Lathe Tools Used in Break Down Test. Note Wear on Front of Tools during Test. Same Tools as Shown in Fig. 3

enough to produce a measurable change in depth of cut. Experience has shown that when the two tools are set at equal depths at the start of the test, the trailer begins to cut when the wear on the leader is between about 0.001 to 0.002 inch. The point at which the trailer begins to cut is taken as the end point of the test or tool failure. As already stated, greater wear may be used to represent tool failure by setting the trailer tool at a shallower depth than the cutting tool. The test is, therefore, applicable to a wide range of cutting conditions.

The wear on a broad nose, high speed steel tool working with shallow cuts begins near the leading edge. The crumbling or wearing away of the nose then progresses from the leading edge to the trailing edge of the tool. This shift in the working proportion of high speed steel tools usually takes place slowly and can be followed quite readily in most cases. It occurs more rapidly with carbon and low alloy tool steels, which are generally ruined very soon after the leading edge shows evidence of crumbling or spalling.

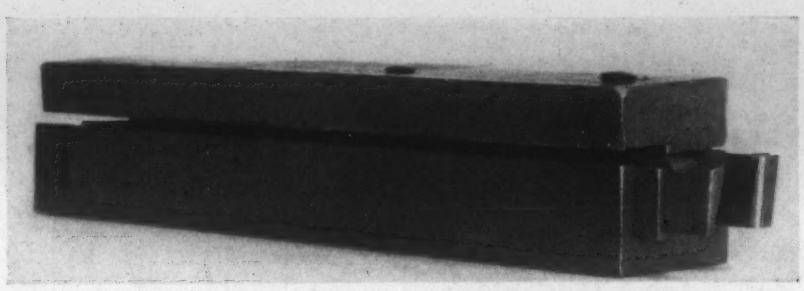

Fig. 6.—Special Tool Holder Used at the Bureau of Standards for Lathe Tests under Shallow Cuts and Fine Feeds

A groove is formed on the top surface of high speed steel tools near the leading edge and vertical grooves are also formed on the face as shown in Fig. 7. The spacing of the grooves on the face corresponds to the feeds used and the length of the grooves is dependent upon the depth of cut. A depression is also formed on the top surface of both carbon and tungsten steel tools but there is often no evidence of the feed grooves after failure.

Experiments have shown that when high speed steel tools failed in a short time the wear of 0.001 to 0.002 inch was concomitant with a complete break down of the tool comparable to that found with deep cuts in roughing turning.

When cutting conditions permit the tool to cut for only a short time this method of testing gives an end point coinciding with tool failure and the trailer tool is unnecessary. However, under more practical conditions where the tools will cut for a long period, the wear on the nose of 0.001 to 0.002 inch is seldom concomitant with tool failure. Under these conditions it becomes impracticable to determine the time of tool failure without an indicator such as the trailer tool.

This test method has been used to establish the relation between the cutting speed, feed, depth of cut, and tool life for carbon and high speed tool steels when cutting $3^1/_2\%$ nickel steel forgings having tensile strengths within the range of 80,000 to 100,000 lbs./in.^{2} It has also been used to study the performance of tools of varying chemical composition when subjected to different heat treatments and the results compared with roughing cuts.

The trailing tool method is also being used at the Bureau of Standards in studying the machinability of carbon and alloy steel forgings having a wide range of mechanical properties. The machinability tests are now in progress and for this reason no very definite information regarding the results can be given at this time. However, the work has advanced far enough to indicate that some very valuable information for the metallurgist and engineer will be obtained when the tests are completed.

The trailing tool method has several decided advantages such as simplicity of equipment, rigidity, and ease of setting up in preparation for the test. Reliable and consistent results can be obtained with a reasonable degree of care in making the test.

The procedure is purely a tool life test and has the disadvantage of not taking into consideration the type of finish left on the work piece. The nature of the finish is one of the most important factors in judging a finishing cut but no satisfactory method has yet been worked out for the evaluation of this factor under the various conditions of cutting, such as turning, milling, etc. However, under otherwise fixed conditions of turning, such as tool form, coolants, feed, and depth of cut, the tools that retain the keenest edge and permit the highest cutting speeds, generally give what appears to be the best machine surface on steel forgings. In this way a measure of tool life furnishes an indirect indication of what may be expected in the type of finish on the work piece. This is to be considered only an approximation for many exceptions may be found.

The same precautions and care are necessary in making finish-turning tests as have already been discussed under roughing cuts.

Experiments have shown that the best tools for finish cuts are not necessarily the best for roughing work. Thus the finish turning test, like the break down test, does not tell the whole story, but it is another chapter added to the study of tool performance and machinability of metals.

DRILL TESTS

Several methods are commonly employed in testing the performance of drills.[2] One method is by testing the drill of a selected form and size under constant conditions of speed and feed. The measure of the endurance of the drill may be taken as the number of inches cut or holes drilled in a standard test piece or the total time that the drill cut before failure. Drills may also be tested by the increment methods. Here the drill is operated at a given feed and speed for a certain depth and then the feed or speed or both increased and the same depth drilled as in the first step of the test. This procedure is continued until failure occurs.

Tests are usually made under rather severe cutting conditions and the speed and feed selected should be such as to produce tool failure within the range of 25 to 200 inches of cutting. The feed and speed selected

[2] The test methods described for drills and milling cutters are from Jerome Strauss. Cutting Tests of Tool Steels, *National Metals Handbook* (1930) page 454.

for such cutting will depend upon the size, form, composition and heat treatment of the drills as well as the properties of the material cut and the coolants used.

Drills have been tested in cutting cast iron, various steel forgings and other metals, but no definite laws have been established for drilling such materials. However, it is possible to make comparisons of drill performance with the relatively short time laboratory life test and predict, with a fair degree of accuracy, the performance under more moderate working conditions in shop practice. Drills that show the best performance in drilling a certain type of material may not be the best suited for a different type of material. Care must, therefore, be exercised in not drawing too broad conclusions from laboratory tests.

As in the turning tests already described, from 8 to 10 tests should be made for each condition investigated and only average results used in making comparisons.

A study of the machinability of various materials has been made by means of drilling tests. Most of this work has been with the penetration test or by measuring the torque and thrust values. Such tests are usually made only with a sharp drill and no tool failure takes place. These methods of measuring machinability give results of value, but since they are not life tests the results will not be discussed in this article.

MILLING CUTTER TESTS

So many difficulties are encountered in testing milling cutters that testing tools of this type have not been extensively used for research purposes as in the case of lathe tools.

Such factors as design and heat treatment of the cutter to produce tools of duplicate cutting performance, machine equipment to prevent vibration, lack of a definite end point of the tool when testing, and the lack of continuous cutting during the testing operation, all add to the difficulty of securing consistent and reliable results.

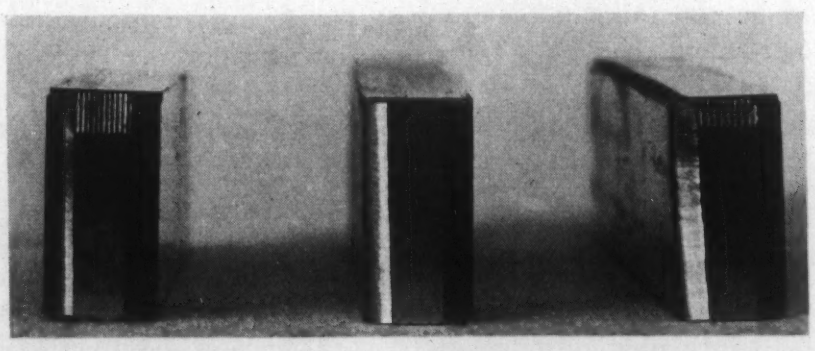

Fig. 7.—New High Speed Steel Lathe Tool and Tools Which Failed under Shallow Cuts and Fine Feeds. Note the Feed Grooves Worn on the Front of Tools during Test

One method of testing tools of this type consists of using a constant speed, feed and depth of cut and determining the number of linear feet cut on a standard test piece until time of failure. The increment test is also used for milling cutters. With this test the cutter operates with a constant depth of cut and at a given speed and feed for a definite linear cut. Then the speed or feed, or both, is increased with the original depth of cut and the same linear distance is cut as in the first step. This procedure is continued until failure occurs.

Tests are usually made under heavy-duty conditions of cutting in order to secure failure in a reasonable period of time. Failure of the cutters is not always readily detected and an arbitrary amount of wear, or increase in the power required in cutting, or increase in forces on the tool, may be selected as the end point of the test. At least three tools on each of two cutters should be made for dependable results.

No very extensive investigation of the machinability of the various metals with milling cutters is known to the writer. As already stated the difficulties encountered in making this type of test as compared with other types of cutting test has discouraged experimental work on this type of cutting. Despite these numerous difficulties, milling cutter tests can probably be carried out to give valuable information in differentiating between good and poor tools for a given job.

MATERIALS CUT

Most of the available information on machinability and tool testing has come from cutting steel forgings and cast iron. In fact, the laws that are now established for cutting are almost entirely confined to the steel alloys. This does not mean that there is or has been a lack of industrial interest in cutting other materials and in the determination of laws of cutting of such materials.

Large quantities of any given material with fairly uniform cutting properties are essential if the laws of cutting for that material are to be determined. The difficulties of securing and the cost of the material, together with the time and cost of carrying out the large number of tests necessary, have been in most cases, too great to warrant the undertaking of such tests. Thus, there is always present the question, "Are there any general laws of cutting applicable to this material?" Apparently, and unfortunately, the answer to this question has too often been in the negative.

Cast iron may be taken as a representative example of a material having a wide range of cutting properties. The machining properties of this material depend to a large extent upon the condition of the carbon in the casting. In the manufacture of the castings the surface usually cools faster than the interior. This results in a product with a hard skin and soft interior. In the hard surface the carbon is at least partly in the combined condition and makes machining difficult. Most of the carbon below the surface is in the free condition and the casting can be cut with relative ease.

The real problem for the machinist in production work is the removal of this outside surface. Besides being hard, the surface often contains flaws and sand. All of these factors are detrimental to tool life and production records. The properties of this outside surface vary so widely that no laws of cutting are applicable nor can any set rule for its removal be established. After this skin is removed the machinist usually has a free cutting casting and the laws of cutting of this material (if any) become of secondary importance.

The hard surface can be fairly accurately controlled by regulating the cooling rate of the casting. However, despite this fact, in a series of castings, manu-

factured under apparently identical conditions there will often be some that are more difficult to machine than others. The removal of this scale at present, namely, since the introduction of the new tungsten carbide cutting tools, is probably not as great a problem in most machine shops as it has been in the past. These tungsten carbide tools are claimed to be especially adapted for this type of work since they have a high resistance to abrasion during cutting. They are also extremely hard, so that the hard surfaces of the casting are not so detrimental to tool performance as is the case with carbon and high speed steel tools.

Cemented tungsten carbide tool material has opened up another field of alloys for the engineer's use. In the past, certain alloys that have desirable mechanical properties have not found a wide application because of the extreme difficulty of machining. Many of these alloys can now be machined on a commercial basis with the new tungsten carbide tools. Research work is very active at the present time in developing and testing this cutting material and in studying its application to industrial work. Much remains to be learned concerning the proper test methods for these tools.

It is rather outside the scope of this article to describe in detail the machining characteristics of the various materials that must be handled in the modern machine shop. These problems are so wide and so varied that an attempt to consider them would not be feasible at this time.

The test methods that have been described are probably those most valuable for producing information for the engineer confronted with the problem of making tool comparisons and of determining machinability. They are by no means applicable to all the cutting problems that arise in the shop for there is no single test that will evaluate the cutting properties of a tool or alloy for all conditions of service.

No very definite relations exist between the turning, drilling and milling tests described so that care must be taken not to make too wide application of the results obtained in one class of cutting to some other class. Likewise, the application of the results for a given test to the cutting of metals differing widely from those used in the test are liable to be misleading.

For more detailed information on the subject the reader is referred to the many references contained in Professor O. W. Boston's "Bibliography on the Cutting of Metals" published in 1930 by the American Society of Mechanical Engineers.

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(Editorial Comment continued from Page 38)

microscope to produce photomicrographs of the structure of metals, whether or not he can interpret them. To some, at least, the term bears about the same relation to that of "metallurgist" as "analyst" does to "chemist." A better term, were it not so cacophonous, would be "metallologist" analogous to "bacteriologist," "geologist," or "physicist."

Whatever we call him, we mean the man concerned with metals as metals, and capable of interpreting and correlating diverse observations, and carrying out decisive experiments to settle points now obscure in relation to the properties of metals. To understand and control those properties of metals and alloys which give them their value as engineering materials, he must be a good deal of a physical chemist, of a physicist and of a materials engineer. He must be able to use and to interpret the data obtained by the microscope, the X-ray, the thermal analysis outfit, the dilatometer, electrical resistance and magnetic methods, all the standard mechanical test methods, and then some special ones to fit the case in hand. He must piece together all the evidence obtained by all these methods, and have perspective enough to know which ones give the most trustworthy testimony in a given case. He must also be conversant with the literature, and especially be able to read technical German in order to keep abreast of the times, and save himself useless work through his utilization of the facts made available by other workers.

If we set up such a requirement for the men who are to carry on the metallurgical developments of the next generation on a sound scientific basis, in industrial research, in institutional research and as teachers, we may well ask whether enough men and those with sufficient training, are being developed.

If we were bold enough to name a few of the youngsters who bid fair to be the Bassetts, Beckets, Burgesses, Jeffries, Sauveurs, Mathews and Mericas of the coming generation, we might cite Bain, Fink, French, Herty, Hoyt, Grossman, Krivobok and Mehl merely to pick a few at random. A flock of other names comes to mind and the reader can go on for himself.

It is encouraging that metallurgy has so many young and virile minds of this caliber. It is essential that, when they in turn become "the elder statesmen" of our profession, still others shall come along to take their places. The names in both lists, jotted down at random as they flashed into our mind, serve very well to point our moral, for these men spent time enough under instruction to get thoroughly and broadly grounded and did not cease their study when they left the academic confines.

No one expects a university to produce full-fledged scientists capable of independent pioneering after a four-year course. The post-graduate work for the doctor's degree, or equivalent training in commercial or institutional research is needed by most men before they can discard their waterwings and start swimming in deep water all by themselves. The industries and the institutional laboratories take pains to facilitate the continued self-education of their men, but they are not primarily educational institutions. They can help people to help themselves, but unless the graduate has learned how to study by himself, and to appreciate that no matter how many degrees he has, he still needs to study, no one can work him over into an A No. 1 product.

The four year-course necessarily has to be pretty much of a stuffing-in process. Real education according to the meaning of the word—to draw out—seldom goes on very effectively in undergraduate work. The ability to draw out of one's own consciousness the correlations needed in modern scientific research comes only as a result either of long accumulated experience or of actual research work under a competent leader.

In chemistry it is becoming realized that four years is not enough in which to give a man the bare facts he must remember (or know where to find) plus the ability to continue his education, so graduate work, or at least a five-year course, is considered almost a prerequisite for men who are to grow into responsible positions in chemical production or research. The physical metallurgist needs nearly as much chemistry as, and far more physics than, the average chemist gets, to say nothing of actual metallurgy.

We have long recognized that physicians, lawyers and ministers need more than four years of college before they are prepared to enter their life work. Metallography is rapidly getting into the same category.

Not only must we find men of the proper stamp to go into metallurgy, and encourage them to pursue academic study and research long enough to prepare them for the demands of modern industry, but modern industry must be willing to pay such men, when they do enter it, a fair recompense for the extra time which they have to spend in their preparation (compared to that of the bond, the insurance and the real estate salesman for instance). And then thought must be given to the perpetuation and support of a teaching staff in the universities that will give both the technical training and the spiritual inspiration needed by the men who will sit at their feet. H. W. G.

READERS' COMMENTS

EDITOR, METALS & ALLOYS:

We have hit upon a useful method of preserving polished specimens for metallographic examination, which is as follows:

From a cigar factory we purchase a package of the cellophane tubes they use for their cigars. These we cut in two as the half of the tube is about of right length for the average size specimen. For temporary preservation the specimen is inserted about half way and the ends of the tube twisted tightly.

Aside from keeping the specimen from tarnishing without the need of storing it in a desiccator, the great advantage of this method is that the etched surface and identification marks can be seen plainly, and if numerous specimens have to be prepared at once any particular one can be identified without unwrapping it or the nuisance of having to withdraw it from a desiccator where not many samples can be accumulated.

A further advantage is the abuse that can take place without danger of marring the prepared surface.

For permanent preservation the flat ends of the tube are sealed for a short distance close to their ends with a cement made of cellulose dissolved in acetone.

We have found no method as convenient as the one described.

Yours very truly,
ENRIQUE TOUCEDA.

Albany N. Y.
January 21, 1931.

To the EDITOR OF METALS & ALLOYS:

In connection with the problem of wear resistance brought up in your correlated abstract on wrought iron in the January issue the following progress report may be of interest.

STANLEY P. WATKINS.

Metallurgist,
Wrought Iron Research Association,
January 25, 1931.

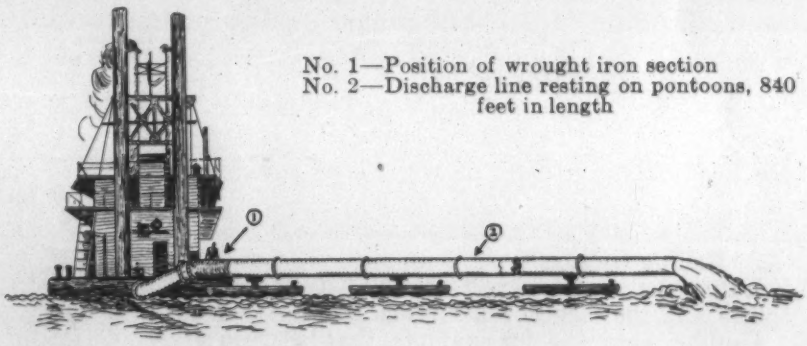
ABRASIVE RESISTANCE OF GENUINE WROUGHT IRON PIPE VERSUS LOW CARBON STEEL PIPE IN A DREDGE DISCHARGE LINE

The following test was conducted with the coöperation of the U. S. Engineers, Louisville, Ky.

The ability of wrought iron to withstand abrasive action has long been recognized, but no actual data as to its relative resistance when compared with steel had heretofore been obtained. With this in view, the U. S. Engineers were asked to insert a section of genuine wrought iron pipe in one of their dredge discharge lines, as the abrasive action is very severe, due to the action of the sand and gravel passing through at a high velocity. The steel pipe used for these discharge lines is of a low carbon grade, electric welded from $^3/_8$" plates, 20" inside diameter and is purchased in 20' lengths. The sections are bolted together with flange connections, flanges being welded to the pipe. Such steel pipe has a life of approximately two dredging seasons, a season lasting from early spring until late fall. Corrosion is no factor in the life of the pipe.

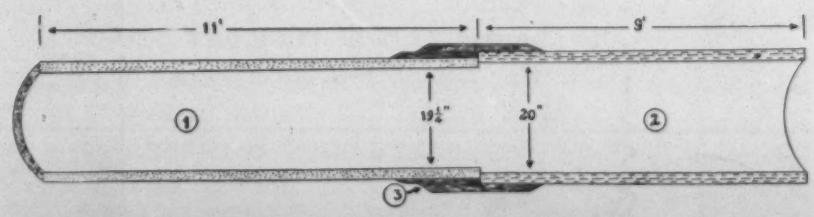
The test section of genuine wrought iron pipe was installed as the first section of the discharge line on the suction dredge "Lake Charles," operating on the Ohio River above Paducah, Ky. The material being moved consisted of sand and gravel, about 70% sand and 30% gravel. The dredge in question pumped 714,000 cubic yards through this line, since the wrought iron pipe was installed.

The following sketches show the method of installation and layout of test.



No. 1—Position of wrought iron section
No. 2—Discharge line resting on pontoons, 840 feet in length

At the end of the dredging season, the test section was examined for signs of wear due to the action of the sand and gravel. The pipe had been in the same position during the entire period; that is, it was not turned to equalize the wear. The greatest amount occurs on the bottom side of the pipe. It is customary to turn the pipe over after each season in order to secure the best possible service life from pipe used in dredge discharge lines.



Showing method of joining wrought iron and steel pipe. (1) Wrought iron (2) steel and (3) steel bands welded on

The total amount of wear of wrought iron and steel pipe was obtained by boring holes in the bottom side and measuring the thickness of the pipe wall.

The results are as follows:

Wrought Iron—No. 1—0.352"	0.277"	Steel—No. 1—0.370
Wrought Iron—No. 2—0.295"		
Wrought Iron—No. 3—0.262"		Steel—No. 2—0.213

The top of the wrought iron section is worn a little more than the steel, but this is due to the manner of connection as shown in the following sketch.

(Continued on Page 56)

WEAR OF METALS*

By Samuel J. Rosenberg** and Harry K. Herschman**

INTRODUCTION

THE development of wear data from service tests is for the most part impracticable because of prohibitive costs, the relatively long periods of time involved, and the difficulty of securing adequate records which include all the important factors during such service. Above all, there is the necessity of promptly evaluating new materials. It is, therefore, essential to resort to laboratory tests in order that the wear resistance of materials may be studied and developed on a satisfactory and extensive basis. The data thus obtained must then be properly correlated and applied to service conditions.

This article will describe briefly, 1. the types of wear, 2. some of the better known wear testing machines, 3. the difficulties encountered in wear testing, and 4. the factors commonly encountered in the application to service of results obtained in the laboratory.

TYPES OF WEAR OF METALS

Wear, for all practical purposes, may be considered essentially a surface phenomenon and is generally said to consist of the gradual mechanical deterioration or tearing off of particles of contacting surfaces through friction. Among the recognized types or causes of wear are the following:

A. Rolling friction

1. Lubricated—as, for example, that between steel rollers and the race in roller bearings.
2. Unlubricated—as, for example, that between a car wheel and rail.

B. Sliding friction

1. Lubricated—as, for example, that between a shaft and a plain bearing.
2. Unlubricated—
   a. Between two solid bodies, as, for example, that between a brakeshoe and wheel.
   b. Between a solid body and an abrasive material of more or less fine grain, as, for example, that to which grinding, crushing or excavating machinery is subjected.

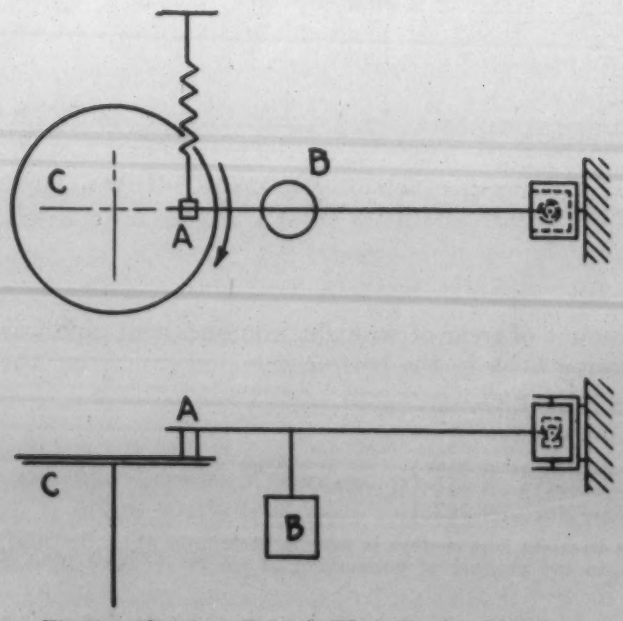


Fig. 1.—Sketch of Robin's Wear Testing Machine

METHODS OF WEAR TESTING

Many machines and methods for wear testing have been developed and used by various investigators. A few of the better-known machines will be described in sufficient detail to indicate the particular type of wear resistance for which they are designed, or are best adapted to study. More detailed information may be obtained from the references to the appended bibliography.[2,5,7,8,10,12,13,11,16,17,19,†]

Probably the most extensive pioneer work on wear testing was that done by Robin[1]. The essential details of the machine used by him are illustrated by the diagrammatic sketch of Fig. 1. Robin's tests consisted essentially of rubbing a steel specimen, A, held under a load determined by the position and mass of a weight, B, against papers covered with an abrasive powder and held on a plate, C. His measure of wear, called abrasion number, was the sum of the weights of metal lost during three consecutive tests, each lasting a minute.

Another machine for determining the abrasion re-

† Numbers refer to references in bibliography.

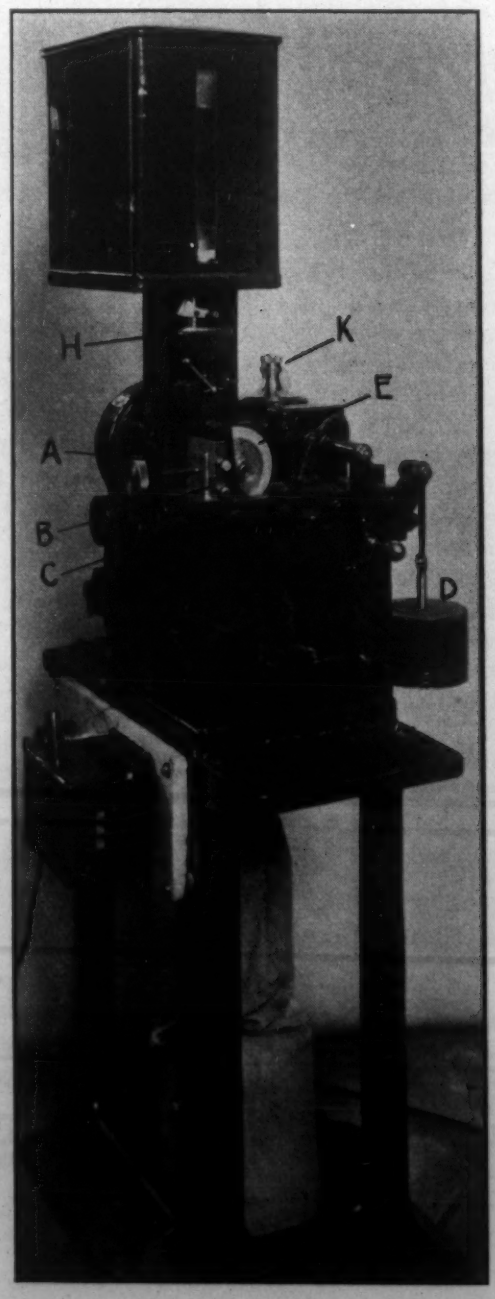


Fig. 2.—Brinell's Wear Testing Machine

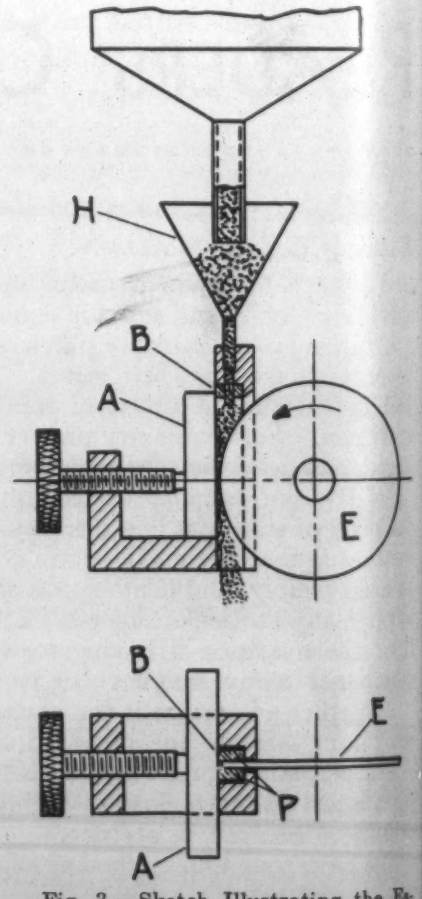


Fig. 3.—Sketch Illustrating the Essential Parts of Brinell's Wear Testing Machine

* Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

** Associate Metallurgist, Bureau of Standards.

sistance of materials is that developed by Brinell[9] shown in Fig. 2. The specimen, A, is clamped to a slotted plate, B, mounted on a carriage, C, to which is attached a cord passing over a pulley and carrying the weights, D. Disk E, of open-hearth iron, 100 mm. in diameter and 4 mm. thick, is so mounted on a shaft that the center line of its face coincides with the center line of the slot, B, against which the specimen is clamped.

In operation, the carriage, C, mounted on ball bearings, moves to the right until the specimen rests against the abrasion disk, the pressure between the two being determined by the weights attached to the end of the slide. A hopper, H, mounted above the slotted plate is filled with sand. The total linear travel of a point on the circumference of the abrasion disk can be adjusted by a graduated wheel and lock nut, K, on top of the machine. During the test a continuous stream of sand is passed between the specimen and the rotating disk.

Fig. 3 is a diagrammatic sketch illustrating the essential parts of the machine. Brinell used as a measure of wear a function of the depth of the groove worn into the test specimen. Rosenberg[21] using the same machine, found that measuring the wear by means of losses in weight was much more reliable.

Perhaps the most generally used wear testing machine is that devised by Amsler[15] shown in Fig. 4. The essential features of this machine are: 1. a gear train so constructed as to give either sliding or rolling friction, 2. a calibrated spring, P, for adjusting the contact pressures between the test specimens, S_1 and S_2, 3. a cam device, C, which may be used to give a lateral sliding motion between the test specimens during test, and 4. a friction dynamometer and torque indicator, T, for determining the work done upon the test specimens and the torque developed during test.

While this machine has most generally been used for dry metal-to-metal tests, it can also be used to test metals in the presence of lubricants by dripping oil from the reservoir, O, upon the specimens. Wear is measured by the losses in weight of the specimens.

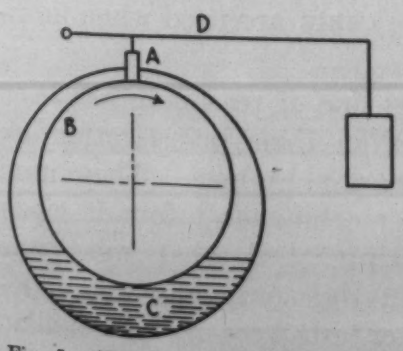


Fig. 5.—Sketch of Derihon's Wear Testing Machine

An apparatus designed especially for the determination of wear in the presence of lubricants is that devised by Derihon[4] shown diagrammatically in Fig. 5. The principle of this apparatus is based upon the determination of the wear between a specimen, A, and the circumference of a polished wheel, B, which turns at a high speed in an oil bath, C. A lever, D, bears against the specimen with a known pressure and as this lever descends in accordance with the wear of the specimen, the latter factor can be determined with the aid of a micrometer screw which is set up on the machine.

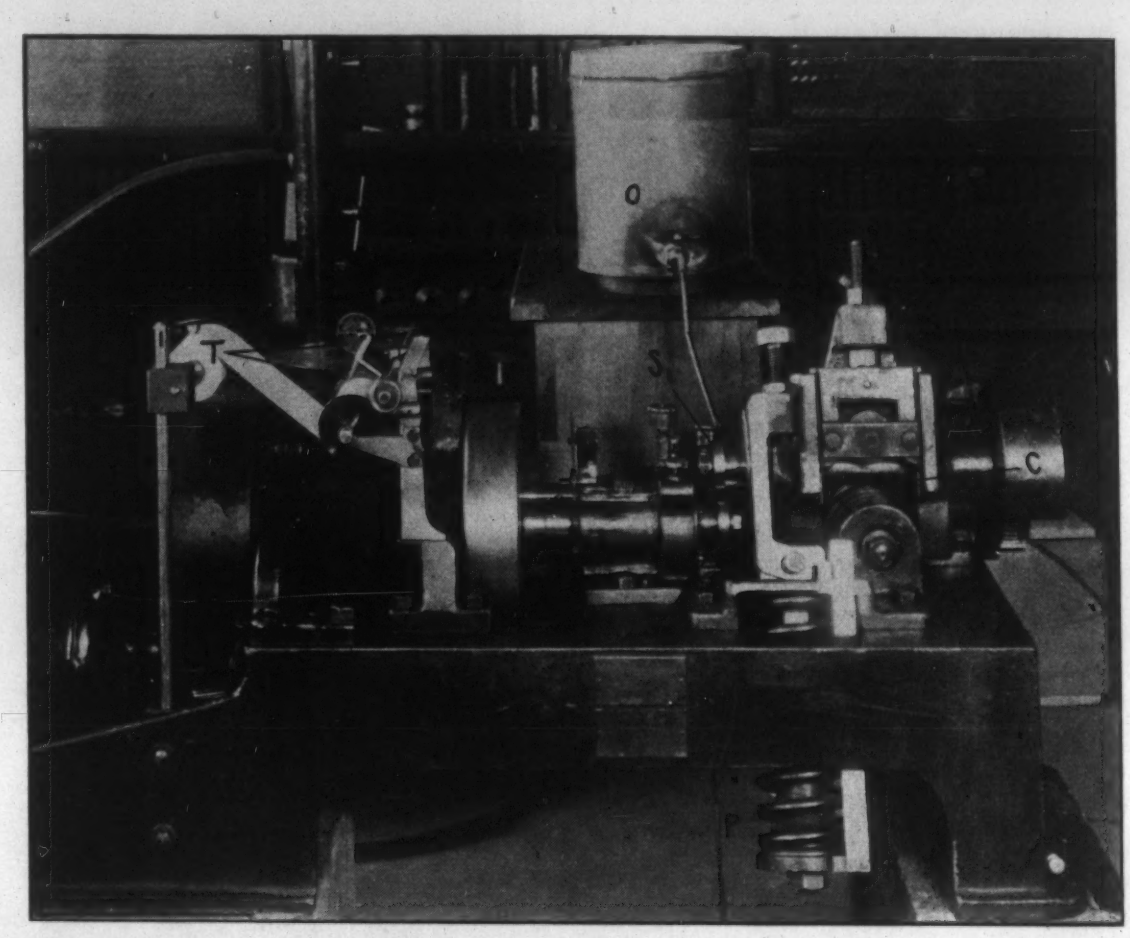


Fig. 4.—Amsler's Wear Testing Machine

A machine for the determination of rolling and sliding friction is that devised by Saniter[3,6] a diagrammatic sketch of which is shown in Fig. 6. A revolving chuck, A, holds the cylindrical test specimen, B, which drives by friction the inner ring, C, of a loaded ball bearing. The outer ring, D, is held tight by an adapter, E, which is hinged on to the loaded lever, F, through the bar, G. The inner ring, C, is made of a 6% nickel steel and has a Brinell hardness of about 555. The Saniter wear number is based on the ten-thousandths of an inch by which the diameter of the test piece is reduced during a definite number of revolutions as compared with the decrease in diameter of a standard bar tested under similar conditions.

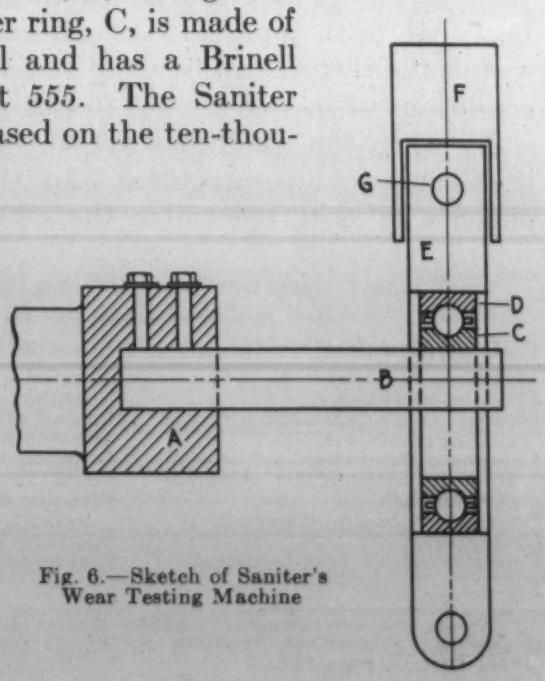


Fig. 6.—Sketch of Saniter's Wear Testing Machine

The plug-gage wear-testing machine, designed by French and Herschman[11,14] and shown in Fig. 7, illustrates the principle of designing a wear testing machine to simulate particular conditions of service. In this machine the cylindrical test specimen, G, is moved vertically in a split ring, J, (see diagrammatic sketch, Fig. 8) by means of piston, P, sliding in the cylinder, C. The piston is threaded at its lower end to provide means for attaching the test gage, G. The contact pressure between the test specimen and the split ring is obtained by springs, L, acting through lever arms, K. Suitable mechanism is provided to permit the horizontal rotation of the split rings. Wear was measured by both the decreases in diameter and the losses in weight of the specimens.

FACTORS AFFECTING INTERPRETATION OF WEAR TEST DATA

The difficulties besetting wear testing and the interpretation of the results obtained are numerous. It is well known that there is no one "best wear-resistant" material for all types of service and conditions. A material which proves satisfactory in one installation is frequently quite worthless in another. This is because of the variations in conditions of service. There cannot, therefore, be a universal wear test. This fact has been recognized by the many investigators who have made a study of the wear of materials and who have used or devised machines for testing the resistance of metals to wear so as to give one certain type of wear or to simulate certain known conditions of service.

A summary of the factors affecting the wear of metals is given in Table 1.* In making wear tests those factors associated with the metals themselves can be more or less fixed but the conditions of service are not so easily duplicated, especially when the conditions are so complex as to make it difficult to separate them into their several components so as to determine the effect of each.

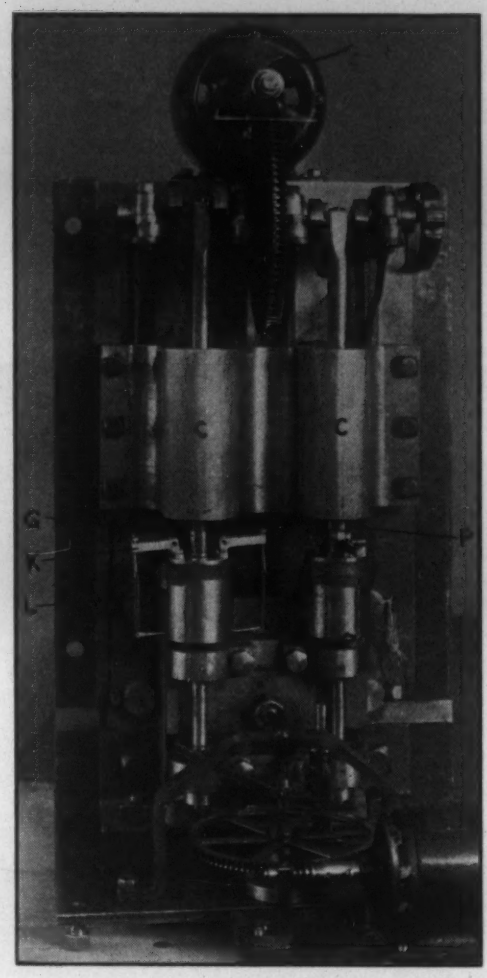


Fig. 7.—Gage Wear Testing Machine Designed by French and Herschman

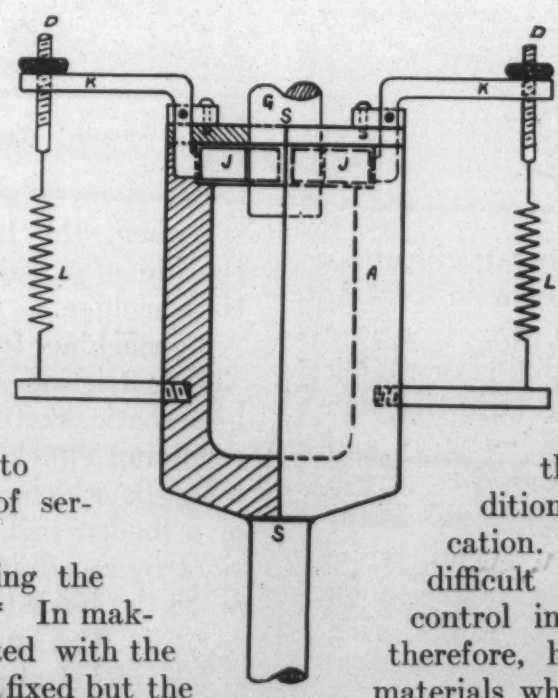


Fig. 8.—Sketch Illustrating Method of Mounting Test Specimens in the Gage Wear-Testing Machine

Table 1—Important Factors Affecting the Wear of Metals

Factors Associated with the	
Metals Themselves	*Conditions of Service*
Metallurgical origin	Material with which the metal is in contact
Chemical composition	Contact pressure
Casting conditions—temperature, chilling effects, etc.	Abrasion speed
Conditions of working—hot or cold, finishing temperatures, direction of rolling, etc.	Duration of abrasion period
Presence or absence of impurities	Condition of surface (smoothness)
Grain size	Presence or absence of lubricants, coolants, abrasives, film, etc.
Constitution and heat treatment	Operating temperature
	Stress-corrosion effects

* Taken, with two changes, from the article by H. J. French, Wear Testing of Metals. *Proceedings American Society of Testing Materials*, Vol. 27 (1927) Part II, page 212.

Furthermore, it must be recognized that the choice of a material for any particular type of service where wear is a major factor cannot always be made upon the basis of wear data alone. Thus, the material used in a tire chain which may show to best advantage in a test devised to simulate the friction suffered by a tire chain may not be the best material for actual service due to the fact that repeated impact plays such an important part in the life of material used for this purpose. In an effort to find the material best suited for this class of service, it would be necessary, therefore, to supplement the wear tests with a suitable impact test and to choose the material having the best combination of properties.

The two factors which probably cause more trouble than any others in laboratory wear tests are those of lubrication and of surface film. These factors will be treated individually.

It is generally accepted that no appreciable wear occurs as long as complete lubrication is maintained between moving parts, assuming that the lubricant is of good quality and does not contain any abrasive matter. Thus, Boegehold[18] found in wear tests conducted on an automobile engine constructed of individual cylinders of four different kinds of cast iron, after running 20,000 miles, that the kind of cylinder iron used had no influence upon the results because of good lubrication between piston and cylinder. Wear between moving metallic parts occurs, therefore, when the oil film breaks down, or under conditions of partial or "boundary" lubrication. This latter condition is manifestly difficult of attainment with any degree of control in a wear test. Most investigators, therefore, have substituted "dry" wear tests for materials which in service are used with lubricants reasoning that since wear occurs only when lubrication fails, wear is a function of the nature of the contacting surfaces and the materials themselves. On this basis it can be logically assumed that a "dry" wear test should show what material is best suited for a given service where lubricants are used when lubrication fails.

The acceptability of this line of reasoning has been shown by French, *et al.*,[15] in their investigation on the wear resistance of bearing bronzes. They used the Amsler wear testing machine and found, when testing these bronzes against steel, that wear was practically negligible when the specimens were adequately lubricated. Further tests were made on similar materials in the absence of lubricants. On the basis

of these latter tests, coupled with other suitable mechanical tests, they were able to single out the bronzes which were generally considered the most satisfactory materials as determined by long periods of usage in service.

Surface films, formed during certain types of wear tests, cause many difficulties and complications. So far the formation of a surface film has been observed only in wear tests where metal-to-metal contact obtains and never in wear tests where non-metallic abrasives are used. These films, although characteristic of the materials under test, usually affect the nature of the test results quite markedly. French, *et al.*,[15] in their investigation on bearing bronzes, observed the formation of a surface film, which, as nearly as they could ascertain, was an oxide of lead. They found that this film acted as a lubricant, decreasing the rate of wear when it was present.

When testing steel against steel in the dry condition, a surface film frequently forms which appears to be an oxide of iron and acts as an abrasive, increasing the rate of wear. An explanation suggested as the cause of these films is that the localized heating accompanying the tearing-off of the small particles from the test specimens is sufficiently great to result in the oxidation of these particles, some of which are subsequently imbedded in the surface of the test specimens. The work of Fink[20] tended to corroborate this hypothesis. He tested carbon steels in the Amsler machine under atmospheric conditions and found that a considerable amount of wear took place. When the same steels were enclosed in a gas-tight cell filled with nitrogen and tested under the same conditions of speed and pressure as before, no wear took place, the test surfaces being smooth and bright at the end of the test. The study, control and interpretation of the results obtained when films form on the surfaces of wear test specimens thus become an important factor in wear testing. It can, therefore, be seen that the removal or non-removal of these films during test should be governed by the service to which the materials under test are to be put. Surface films have been removed, or prevented from forming, by means of the use of thin metallic strips scraping against the surfaces of the specimens, by the impinging of a stream of air at the surfaces of contact between the specimens, or by keeping the surfaces of contact wet by a liquid of low lubricating quality such as kerosene or a dilute solution of potassium dichromate.

An important factor which should not be lost sight of is the surface finish of wear test specimens. Thus, the finish of the surfaces of the test specimens, especially in wear tests where metal-to-metal contact exists, should be the same as the finish on the object of the same material when used in service. This is particularly important in wear tests under relatively low pressures.

Erroneous results are frequently obtained when only a few wear tests of relatively short duration are made on any one test specimen. This is due to the fact that these initial results are greatly influenced by the surface finish of the test specimen. It is only when the surface of the test specimen has become "worn in" that wear test results indicative of the wear resistance of the material itself are obtained.

The pressure between wearing surfaces may have a marked effect upon the wear resistance of the metal. In addition to increasing friction, a marked change in the physical structure of the metal may take place during the wearing operation. This change is most frequently referred to as work hardening and is caused by internal strain. When this phenomenon occurs, the outer, or wearing layer, of the metal may show improved resistance to wear due to this physical change.

Portevin and Nusbaumer[4] using the Derihon abrasion mill, found that a work-hardened skin was formed on their specimens which reduced the rate of wear until the limit of such formation was reached when breakdown occurred and wear increased. This breakdown was said to be due to the fact that the limit of tenacity of this work-hardened layer was reached.

Another example of the effect of work hardening of a metal is the change which takes place in high manganese steel (12 to 14% manganese). When this steel is used under severe service conditions, such as jaws for rock crushing machinery, work hardening takes place which produces a phase change in the structure of this steel and results in hardening of the metal with a consequent increased resistance to wear.

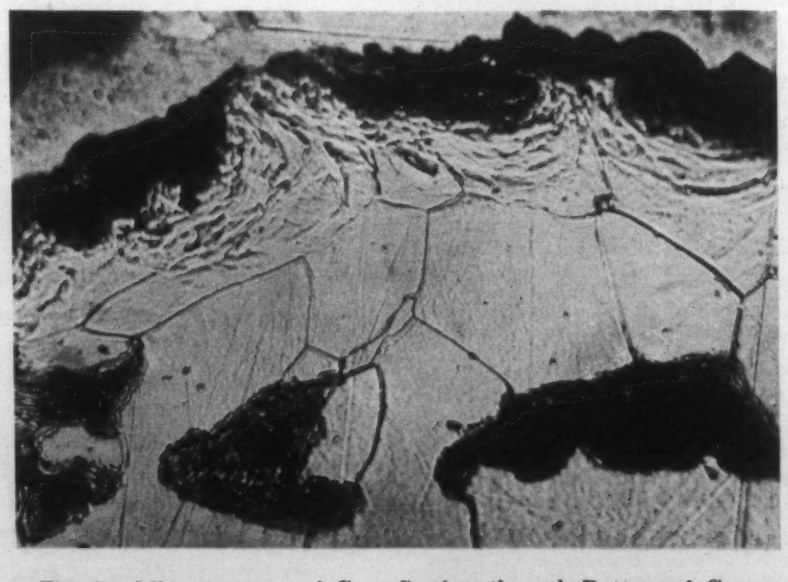


Fig. 9.—Microstructure of Cross-Section through Bottom of Graove Worn into Annealed 0.20% Carbon Steel Tested in Brinell's Wear-Testing Machine. Etched with 2% Nitric Acid in Alcohol. Magnification 500 ×

The manner in which wear takes place is a matter of interest to all investigators. It is generally considered to consist of the detachment of minute particles from the wearing surface through friction. Rosenberg[21] studied the microstructure of a section cut through the bottom of a groove worn into a steel specimen when tested in the Brinell machine. An examination of this section revealed the fact that the mechanism of wear in this particular case took place by parts of individual grains being abraded and not by grains being torn out in their entirety, this abrasion being accompanied by severe local straining. The structure of this sample is shown in Fig. 9.

An attempt is usually made by most investigators to establish a relation between the wear resistance of metals and one or more of their mechanical or physical properties. Most frequently the property chosen for comparison with wear is the hardness[5] of the material tested. The harder materials frequently ex-

hibit a higher degree of wear resistance than the softer materials, but in any one application this order may be found to be reversed. Little, if any, definite relation has been found to exist between wear and other mechanical properties.

The ever increasing interest in the wear of metals during the past two decades has definitely indicated the importance of this subject. During the course of this period many investigators have made detailed studies of this subject both in the laboratory and in service. However, the data available from these investigations are so varied and scattered as to make it extremely difficult for the engineer to find in any one source the information which he desires. From this, it is evident that there is a need for a critical review and correlation of the existing data, a task which might well be undertaken or sponsored by one of the engineering societies.

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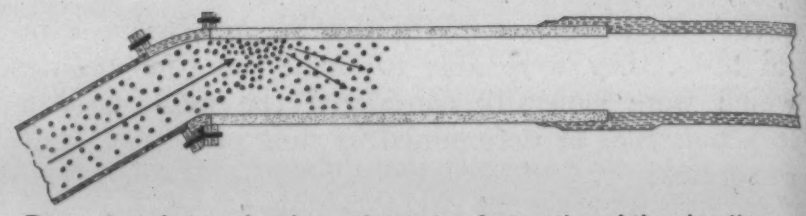
(Readers' Comments continued from Page 51)

In determining the relative abrasive resistance of the wrought iron and steel pipe, it was assumed that the original thickness of the pipe wall in both cases would be 0.375″ as both sections were new and stated by the manufacturer to be 3/8″ wall thickness.

Taking the original bottom wall thickness and subtracting the thickness after completion of the test, the loss due to abrasive wear is easily arrived at.



Due to fact that sand and gravel entering first section of the pipe line are shot up, due to the curvature of the line, it is to be expected that the wear would be slightly greater at this point.

Wrought Iron Pipe	
Original wall thickness	0.375″
Average wall thickness after test	0.277″
Loss of thickness	0.098″
Steel Pipe	
Original wall thickness	0.375″
Wall thickness after test	0.213″
Loss of thickness	0.162″

The wear on the steel pipe was 0.064″ greater than on the wrought iron pipe, which, expressed in percentages, represents 65% greater wear. As the exact dimensions of the original pipes are not known and in order to damage the pipes as little as possible it was not desired to bore more holes at the present, this figure is to be taken as only approximate, but as giving some indication of the behavior to be expected.

Conclusions: The section of wrought iron pipe was installed as the first joint of the discharge line, which receives the most severe action, due to the velocity of the material at this point; also, the wrought iron section was 3/4″ smaller inside than the steel pipe, which would tend to increase the action on the wrought iron, due to the restriction of area. The engineer in charge stated that this was not a fair test of wrought iron due to its smaller inside diameter, but was about the most severe one that could be devised.

It would be worth while to conduct further tests of this nature by placing a section of wrought iron pipe of the same inside diameter as the steel pipe, near the center of the line where the action would be more nearly the average.

This test indicates that wrought iron resists this type of abrasion better than ordinary low carbon steel commonly used for pipe making. It is obvious that wrought iron cannot be compared with materials specially prepared for abrasive resistance. The resistance of wrought iron to such abrasive action is probably due to the presence of incorporated slag particles embedded in a soft, tough matrix. It is a well-known fact that materials that are soft and tough, as a rule, are better suited for resisting abrasive action than harder ones.

The worn surface of the wrought iron and steel was smooth, and no pitting could be noted in either, due to uneven wear.

This section of wrought iron will be examined again at the end of next season, when a more complete set of measurements will be taken and analyses of samples from the worn sections of the competing materials will be made.

Nov. 14, 1930. STANLEY P. WATKINS.

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Cementite Crystal Structure

EDITOR, METALS & ALLOYS:

The interest that the crystal structure of cementite has aroused is not at all surprising. In view of recent comments by your readers it seems proper at this time to call attention to an article by Sterling B. Hendricks on "The Crystal Structure of Cementite" which appeared in *Zeitschrift für Kristallographie*, Vol. 74(1930) page 534. Here the crystal structure was determined from data already recorded in the literature, supplemented with laboratory work. The space group is V_h^{16} for both carbon and iron atoms. Eight iron atoms are at

$x\ y\ z;\ \overline{x}\overline{y},\ z+\tfrac{1}{2};\ \overline{x}+\tfrac{1}{2},\ y+\tfrac{1}{2},\ \overline{z}+\tfrac{1}{2};\ x+\tfrac{1}{2},\ \overline{y}+\tfrac{1}{2},\ \overline{z};$

$\overline{x}\ \overline{y}\ \overline{z},\ xy,\ \overline{z}+\tfrac{1}{2};\ x+\tfrac{1}{2},\ \overline{y}+\tfrac{1}{2},\ z+\tfrac{1}{2};\ \overline{x}+\tfrac{1}{2},\ y+\tfrac{1}{2},\ z;$

and four are at

$u\ v\ \tfrac{1}{4};\ \overline{u}\overline{v}\tfrac{3}{4};\ \overline{u}+\tfrac{1}{2},\ v+\tfrac{1}{2},\ \tfrac{1}{4};\ u+\tfrac{1}{2},\ \overline{v}+\tfrac{1}{2},\ \tfrac{3}{4};$ where $x = .34$; $y = .17$; $z = .065$; $v = .05$; $u = -.16$

Four carbon atoms are placed at $000;\ 00\tfrac{1}{2};\ \tfrac{1}{2}\tfrac{1}{2}0;\ \tfrac{1}{2}\tfrac{1}{2}\tfrac{1}{2}$, from considerations of the probable geometrical configuration. This gives the Fe-C distance around 1.9 A. U., the Fe-Fe distance 2.4 to 2.7 A. U. and the radius of C atom ca. 0.6 A. U. This structure is believed to be non-ionic in type.

Bureau of Standards, P. R. KOSTING,
Washington, D. C., Research Associate.
January 22, 1931.

Adhesion of Electroplated Coatings[1]

By W. Blum[2]

I. INTRODUCTION

One essential requirement of any protective coating is that it should adhere with reasonable permanence under the conditions to which it is subjected. Failure to do so is made evident by flaking or peeling of the deposit. Such failure not only detracts directly from the appearance and service of the article, but also permits corrosion of the base metal thereby exposed, which in turn may cause further peeling of the coating.

The present extensive use of chromium plating over a coating of nickel has accentuated the importance of good adhesion, as there is a marked tendency for the nickel deposit to be detached during the process of chromium plating. This tendency can be and has been largely overcome by suitable modifications of the cleaning and nickel plating processes. Such developments are empirical, but they may serve to illustrate the principles involved.

II. METHODS OF TEST

No exhaustive or very conclusive measurements have been published upon the adhesion of plated coatings. One reason for this dearth of literature is the difficulty of developing reliable quantitative tests for adhesion of thin layers. The only methods that are even promising are those which depend upon deformation of the base metal and observation of the behavior of the coating. On sheet metal this deformation may be accomplished by a simple bending test, e. g., in a vise or over a mandrel of specified diameter. Another method is to apply the Erichsen extrusion test to the coated sheet, and to observe whether the coating has flaked or peeled when the base has failed. A modification of this method has been applied to chromium-plated cast-aluminum alloys in a few unpublished tests made at this Bureau. In these tests indentations were made by the ball of a Brinell testing machine with increasing loads, until it was evident that the chromium coating had detached. The results were roughly reproducible and appeared to have some significance. At best, however, such tests usually show that under given conditions the coating does or does not adhere; and yield little or no information regarding the relative adherence.

Another method that has been employed[3] is to solder a metal strip to the plated coating and to then determine the load required to detach the coating. This method is subject to the fundamental objection that the soldering operation may change the adhesion and physical properties of the coating and thus yield erroneous results.

Suggested methods which depend upon some mechanical means of grasping the coating, and upon measuring the load required for its detachment, necessarily involve the use of very heavy plated coatings. The results may then be valid for thick deposits, but have no necessary relation to the adherence of the thin coatings usually employed in commercial plating, and in which the forces of adhesion and cohesion may be very different from those in thick layers deposited under the same conditions. This difficulty may be more fully appreciated when it is realized that few commercial plated coatings are more than 0.001″ (0.025 mm.) thick, and that the present chromium deposits on automobile fixtures are about 0.00002″ to 0.00004″ (0.0005 to 0.001 mm.) thick.

III. GENERAL PRINCIPLES

In the absence of quantitative tests of adhesion, most of the published statements on this subject, including those in this paper, are opinions that are based either on general principles or on qualitative observations and commercial experience.

In any given case the adhesion of a plated coating must be the resultant of the forces with which it is attracted to the base metal, and those which tend to cause its separation. The latter include not merely external influences such as mechanical deformation and temperature changes, but also those internal forces, inherent in the coatings, which tend to cause the latter to contract and to separate from the base. The two major factors may be conveniently designated as (*a*) properties of the boundary, and (*b*) properties of the coating.

a. Properties of the Boundary:

At the boundary the maximum adhesion, i. e., adhesion equal to the strength of the metal itself, would be expected only if the coating is in actual atomic contact with the base. That such a condition is not merely hypothetical is shown by the fact[4] that upon a properly cleaned surface of copper it is possible to deposit copper in which the crystals present in the base continued to grow in the coating, regardless of whether the base consists of rolled, cast or annealed copper. While no tests of adhesion were made on such deposits, it is reasonable to assume that it is practically perfect, i. e., there is no more reason for the metal to separate at the boundary than on any other plane.

It is at least possible that continued growth of the base metal crystals in the deposit may occur when the two consist of different metals, in fact Graham in his first paper cited above found indications of the reproduction of crystals of brass in copper deposited upon it. A similarity in crystal systems and lattice spacing of the two metals should favor such crystal growth.

The suggestion has often been made that good adhesion of plated coatings may depend upon alloying of the two metals at the boundary. In some cases such

[1] Publication approved by the Director of the National Bureau of Standards.

[2] Chemist, U. S. Bureau of Standards.

[3] C. F. Burgess. *Electrochemical & Metallurgical Engineering*, Vol. 3 (1907) page 17.

[4] W. Blum & H. S. Rawdon. *Transactions American Electrochemical Society*, Vol. 44 (1923) page 305. A. K. Graham. *Transactions American Electrochemical Society*, Vol. 44 (1923) page 427; Vol. 52 (1927) page 157.

alloying probably occurs. Thus prior to silver plating on copper and brass it is customary to use a "mercury dip," which produces a film of mercury or of an amalgam on the surface. When silver is subsequently plated upon this surface, it is reasonable to suppose that the mercury diffuses into both the base metal and the coating and converts the boundary plane into a boundary zone. It has been shown[5] that at slightly elevated temperatures a copper coating diffuses into a zinc base to such an extent as to destroy the copper color of the surface. It was also reported that even at ordinary temperature this process of alloying between zinc and copper takes place, though more slowly. Such alloying of a plated coating as may occur is merely an evidence of intimate metallic contact, and does not necessarily lead to any greater adherence than if the atoms of the two layers were in equally close contact but not interpenetrating. In either case, atomic forces are involved.

Conversely, lack of adhesion may reasonably be attributed to the presence at the boundary of some third phase which has a lower tensile strength than either of the metals. In common parlance, a plated coating will not stick to a "dirty" surface. The very great importance attached in the plating industry to the cleaning and pickling processes prior to plating is evidence of this conviction. One difficulty in evaluating various cleaning processes is that of defining a "clean" surface. The common practice of platers to clean metals till there is no "water-break" affords fairly good evidence of the absence of "grease." It is not, however, an indication of the absence of adsorbed soap or alkali, which by reducing the surface tension would tend to prevent a water-break. That such films may be present on apparently clean surfaces and may reduce adhesion of subsequently deposited coatings, is apparent from the fact that one of the most effective treatments just before nickel plating on brass or zinc-base die castings is a dip in dilute acid. As the latter produces no visible etching, it is reasonable to suppose that the improved adhesion is due principally to the removal of alkali or soap.

The importance of a clean surface when adhesion is desired is indicated by the very small thickness of the films intentionally applied to produce separation of an electrodeposited layer, as in electroforming. Thus when graphite is rubbed over a polished metal surface to permit separation, the amount of graphite left on the surface is so small as to be almost unweighable. Films of sulphide or chromate applied for this purpose are extremely thin. Even adsorbed gas films may promote such separation. Anodic treatment of nickel or steel in alkali is sometimes used for this purpose. The fact that electrodeposits will not readily adhere to chromium or its alloys, i. e., to passive surfaces, is probably due to oxygen or oxide films on the passive metal. An apparent contradiction is found in the good adhesion reported when steel is first cleaned by the "Madsenell" process, which involves anodic treatment in strong sulphuric acid.[6] Further study would be required to determine conclusively whether this treatment is effective because it removes hydrogen and other gases from the steel (as has been claimed), or whether it produces slight etching and roughening of the steel.

The difficulty of producing adherent metal plating on aluminum and its alloys is almost certainly due to the presence of an oxide film on the surface. This is so tenacious and forms so quickly, that the only practical methods of plating on aluminum involve an acid treatment which etches the metal so as to roughen the surface, and thereby promotes mechanical adhesion.[7]

b. Properties of the Coating:

As previously indicated, all electrodeposited metals show a tendency to contract during deposition. This tendency is most marked with those metals such as nickel, cobalt, iron, chromium and platinum, which absorb much hydrogen during deposition. Such absorption produces strains not only during the deposition, but also during the succeeding period when the hydrogen is gradually escaping. This tendency to contract also exists to some extent with the other metals such as copper and zinc,[8] in which hydrogen is not absorbed to so great an extent. With these soft metals, however, any strains set up are readily released because of the low tensile strength of the coating. The magnitude of the strains produced with hard metals may be realized from the fact that depositing about $^1/_4$ inch (6 mm.) of nickel or iron on one side of a $^1/_4$ inch (6 mm.) case-hardened steel printing plate, may bend the latter as much as $^1/_4$ inch in a foot (6 mm. in 30 cm.). The obvious and successful remedy in this process was to fasten two plates back to back, and to deposit on both sides of the combination. The fact that the reproduced plates do not bend appreciably after separation, shows that the strains produced during the plating exceed the elastic limit of the deposited nickel or iron.

If, as is apparent from the preceding discussion, perfect cleaning of the base metal, and hence perfect adhesion of the deposit, is an ideal condition that is difficult to realize in practice, it is desirable to reduce as much as practicable the strains set up in the deposited metal. Here again there is a dearth of quantitative information, but theory and experience have led to definite improvements. In general it may be predicted that relatively soft, ductile metal coatings will be deposited under those conditions which involve the lowest cathode polarization[9] and the highest cathode efficiency. These are (*a*) a high metal and metal ion concentration in the solution, (*b*) agitation, (*c*) a relatively high temperature and (*d*) a relatively low current density. These conditions are now approximated in large plants (e. g. in the automobile industry) where nickel is being plated in mechanical conveyors. To be sure, such plants use current densities that are much higher than those commonly used in still-plating tanks at ordinary temperature. But even these high current densities are much lower than might be used in the warm baths. That these current densities are "relatively low" is evident from the fact that the deposits

[5] J. Haas, Jr. *Brass World*, Vol. 14 (1918) page 36. W. B. Traub. *Transactions American Electrochemical Society*, Vol. 42 (1922) page 55.
[6] F. M. Dorsey. *Industrial & Engineering Chemistry*, Vol. 19 (1927) page 1219.
[7] H. K. Work. *Transactions American Electrochemical Society*, Vol. 53 (1928) page 361.
[8] W. Palmaer & A. Wejnarth. *Zeitschrift für Elektrochemie*, Vol. 29 (1923) page 557. O. C. Ralston. *Transactions American Electrochemical Society*, Vol. 47 (1925) page 193.
[9] W. Blum & H. S. Rawdon. *Transactions American Electrochemical Society*, Vol. 44 (1923) page 397.

are usually dull and soft. In general bright nickel deposits (such as are produced with addition agents) are relatively hard and brittle; and are not suitable for subsequent chromium plating.

The conditions used for chromium plating influence not only the properties of the chromium deposit itself, but also its tendency to detach the underlying nickel. While the factors which govern the structure of chromium deposits are similar to those in other metal deposition, their effects are more critical. It has been reported[10] that if chromium is deposited at relatively high temperatures, or is subsequently heated, the coating furnishes better protection against corrosion. Recent unpublished results of tests at this Bureau have confirmed this observation, and have shown that when chromium is deposited at a high temperature (e. g., 65° C.) and as low a current density as will yield bright deposits, there is an almost complete absence of cracks in the coating. This improvement is probably caused by lower solubility of hydrogen in the chromium at the higher temperature, and not by any decrease in the evolution of hydrogen. Actually the cathode efficiency for bright chromium deposits is always about the same (8 to 18%). It is reasonable to suppose that freedom of the chromium deposit from strains that cause it to crack will also reduce any tendency for it to lift the under-lying nickel coating.

One of the most severe tests of adhesion of electroplated coatings is involved when the latter are required to resist abrasion or impact. In the use of chromium on gages and dies, cracking and flaking of the chromium are sometimes encountered. To overcome this tendency, thorough cleaning of the base metal is necessary. Chromium for abrasion-resistance is usually applied directly to the steel. It has been found that one of the most effective methods of cleaning the steel, especially if the latter has been hardened, is to make the steel anodic in the chromic acid bath for about a minute just before plating. This treatment not only eliminates foreign matter such as grease, but also probably removes any free carbon on the surface that may have come from the heat treatment.

The conditions used to produce chromium deposits that are most nearly free from cracks and strains, i. e., a high temperature and (for that temperature) a relatively low current density, are likely to reduce somewhat the hardness as measured by the scratch method. It might, therefore, be expected that such an attempt to improve the adherence of the deposits would result in a loss in wear-resistance. Recent tests at this Bureau by H. K. Herschman[11] have shown, however, that appreciable differences in scratch-hardness have very little effect upon the wear-resistance of chromium plated plug gages. In fact he found that gages that were plated with chromium and then heated to 300° C. showed the best resistance to abrasion. This indicates that the wear depends even more on the "toughness" than upon the "hardness" of the chromium. Hence, there is no objection to increasing the adhesion by reducing the strains in the chromium.

The same conclusion may be drawn from tests on coinage dies at the U. S. Mint in Philadelphia. These showed that under the severe conditions used, much better adhesion was obtained with thin than with thick chromium deposits. The latter have more cracks and greater strains, and therefore detach more readily under impact.

[10] R. J. Wirshing. Preprint 58–19, *American Electrochemical Society* (1930) 4 pages.
[11] *Bureau of Standards Journal of Research*, Research Paper 276.

IV. CONCLUSIONS

The best adhesion of plated coatings may be expected when (*a*) the metal surface is absolutely clean of all foreign material including grease, oxide, alkali, or soap; and (*b*) the deposited metal is free from strains.

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Committee on Industrial Gas Research Announces the Inauguration of Two New Metallurgical Research Projects

Following its plan of systematically conducting research in the application of heat in all the important metallurgical fields, the Committee on Industrial Gas Research, F. J. Rutledge, Chairman, has just had contracts signed for two new projects. These two new projects are: Research in Deterrent Effect of Scale in Gas Fired Furnaces at Heat Treating Temperatures and Research in Factors Affecting Short Cycle Malleablizing.

The tentative program in the Deterrent Effect of Scale at Heat Treating Temperatures is as follows:

1. A compilation of a bibliography of previous work on the subject.
2. The determination of the relative scaling action of carbon dioxide, moisture, air and oxygen.
3. The consideration of the relative scaling action of mixtures of carbon dioxide and moisture.
4. A study of the equilibria conditions between steel, hydrogen and moisture at heat treating temperatures.
5. An investigation of the equilibria conditions between carbon dioxide, carbon monoxide and steel.
6. The determination of the effect of pressure on scaling.
7. The determination of the effect of rate of flow on scaling.
8. The determination of the effect of period of exposure on scaling.
9. The determination of the physical characteristics of scale and the conditions producing the various characteristics.
10. The study of the effect of the physical characteristics of scale on decarburization.
11. The investigation of the effect of various gas-air mixtures on steel.
12. The determination of the relative scaling characteristics of the more common steels.

The Research in Factors Affecting Short Cycle Malleableizing is prompted largely by recent developments in this branch of the cast iron foundry industry.

This research will tie in very closely with a project being sponsored at the University of Michigan by the Malleable Iron Institute on the machinability of malleable castings.

The tentative outline of the work to be done in this research is as follows:

1. Make a patent search and bibliography.
2. Obtain costs of annealing by the present process using pulverized fuel in order to know whether any saving might be obtained if this process could be accomplished in a short time through the use of gas heating.
3. Determine what is the shortest time and how closely the temperature must be controlled in order to produce proper malleabilization.
4. Determine whether the decarburization that will be produced is serious enough to require steps to eliminate it.
5. Determine what advantages would result in entire elimination of scaling and decarburization.

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Meeting of Committee on Exposure Tests

A meeting was held in Chicago, January 16, of a special joint committee consisting of representatives from the Research Committee of the American Electro-platers' Society from the Sub-Committee on Field Tests of Metallic Coatings of the A.S.T.M. Committee on Corrosion of Iron and Steel, and from the A.S.T.M. Committee on Corrosion of Non-Ferrous Metals and Alloys, under the chairmanship of Dr. Wm. Blum, Bureau of Standards, to consider a program of exposure tests on plated coatings at the localities at which the various A.S.T.M. exposure corrosion tests are being carried on.

TESTING CHROMIUM PLATE FOR RESISTANCE TO ABRASION

By Harry C. Wolfe*

THE increasing number of applications of fairly heavy deposits of electro-plated chromium for resistance to wear and abrasion has made it necessary for those engaged in "hard" chromium plating to make a careful study of the qualities of their chromium deposits. The qualities which are of importance to the electro-plater are: (1) Hardness or, more exactly, wear resisting quality; (2) Ductility; and (3) Protection against corrosion. None of these qualities is of importance in "lustrous" chromium plating which is widely used on automobile trimmings and plumbing fixtures, etc. In lustrous chromium plating the chromium plate is so thin—on the order of 0.00001" that the hardness and ductility of the deposit have no influence; and corrosion protection of the base metal is obtained by intermediate plates of copper and nickel. The only important property of chromium for lustrous plating is that of non-tarnishing.

In the early stages of commercial chromium plating it was realized that the chromium deposit was hard and that there were possibilities of its application for wear resistance. But the chromium plating solutions were developed for lustrous plating and it was assumed that "chromium was chromium"—that any one chromium plate would have the same qualities of any other chromium plate. However, research and experimental work by those interested directly in hard chromium plating has shown that the 3 qualities of chromium plate mentioned above will vary over a wide range with changing factors in the plating solution and plating operation. Although ductility and corrosion protection are of importance and the success of many applications depend upon their proper control, the property of greatest importance is hardness, or wear resisting quality.

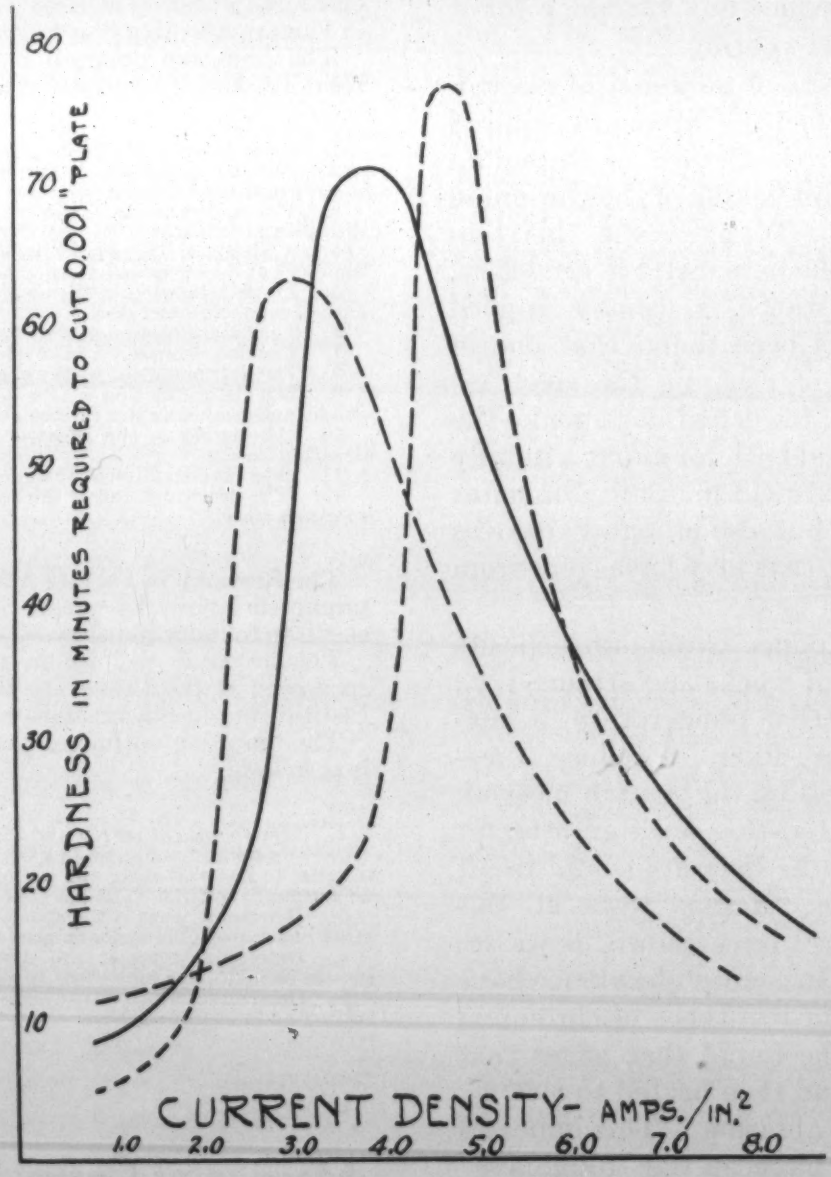

Fig. 1.—Effect of Current Density on Hardness of Chromium Plate. Dotted Curves Show the Position of Peak Changes with Variation of other Plating Conditions

Preliminary investigation showed that the hardness of the chromium deposit is affected by the temperature of the solution, the current density at which the chromium is deposited, the solution make-up and proportion of chemicals in the solution, and other variable factors. Fig. 1 is a curve showing the relation between the hardness of a chromium deposit and the current density at which the chromium was deposited. The results are from tests made after the abrasion testing apparatus was developed. The curve gives some idea of the difficulty involved in the proper solution of the problem. The solid line is for optimum plating conditions. By varying other factors such as temperature and solution make-up the peak of the hardness-current density can be moved vertically or horizontally within limits as shown by the dotted curves. Similarly, most of the other factors that influence the hardness of the chromium deposit are critical so that there is a very narrow range of conditions where best results are obtained. This makes it necessary to closely control all of the factors that affect the quality of the chromium plate.

In order to provide close control for the variable factors in the plating operation it was necessary to obtain a fair approximation of the relative hardness of chromium deposited under different conditions. An abrasion testing apparatus was developed to measure the hardness of the different deposits. The ordinary hardness testing machines cannot be used on chromium plate because of the thinness of the deposit. Even a plate of 0.010", which is a heavy plate, will permit those machines that test by impact or indentation to break through the deposit and thus give an indication of the hardness of the metal on which the chromium is deposited rather than the chromium itself. Also, it was realized that a test which measures hardness by impact or pressure does not give a true measure of the abrasion resisting quality. The scratch hardness test was not considered sufficiently reliable for comparative tests.

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The apparatus which was used for making the hardness determinations is sketched in Fig. 2. The apparatus consists essentially of a standard grinding wheel 2″ in diameter with 1/4″ face which is operated at a speed of about 10 ft./min. The test specimen rests horizontally upon the abrasive wheel and a net weight of three pounds is applied 12″ from the axis of the wheel. The abrasive wheel is cleaned continuously with a sharp pointed steel disc wheel cleaner such as is usually used for this purpose. A dial gage measures the depth of the cut directly to 0.0001″.

This machine gave results that could be reproduced within 10% if care was taken in the operation. If the wheel is permitted to "load up" there is a constantly increasing error although a check of the results may show that they are consistent. The abrasive wheel and the wheel cleaning device are changed frequently and repeated tests are made with different wheels and wheel cleaners. Methods of cleaning the abrasive wheel other than with the steel disc wheel were not satisfactory. For example, when pumice stone is used to clean the wheel, the wheel soon loads up and the results vary over a wide range. The wheel will also load up if no attempt is made to clean the wheel, and additional variation in the results is caused by particles of chromium becoming imbedded in the abrasive wheel and acting as a lap on the chromium plate.

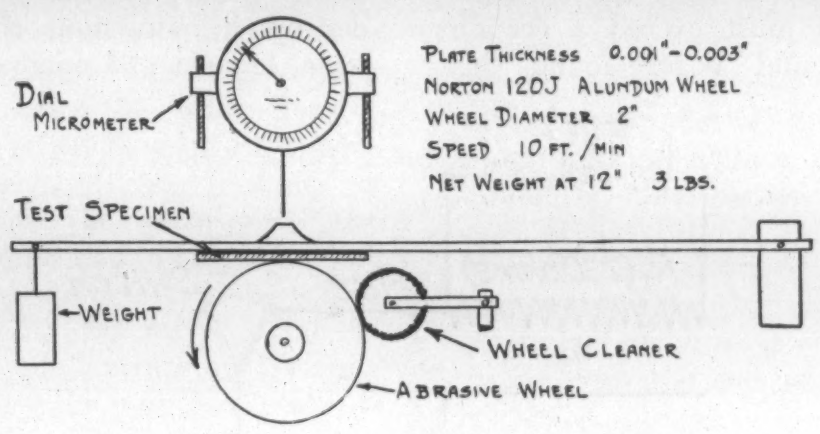

Fig. 2.—Abrasion Testing Apparatus for Measuring the Resistance of Chromium Plate to Abrasion

Low speeds on the wheel were used in order to obtain more nearly an abrasive than a cutting action. Although all abrasion may be considered cutting, it was believed to be desirable to remove the chromium in small particles rather than large particles. At high speeds there is a tendency to dig out large particles of chromium due to the momentum of the abrasive particles. This fact was well demonstrated in testing chromium plate in which the characteristic strains had been relieved as compared to chromium plate in which these strains had not been relieved. The brittle chromium plate was removed in larger particles and the test showed that apparently this plate was less resistant to abrasion than a plate in which the strains are removed.

The depth of the cut is in the neighborhood of 0.001″. The final measurement of the depth is checked by measuring the length of the cut and computing the depth and also by direct dial gage measurements after the test sample is removed from the apparatus. The time required to cut through 0.001″ plate increases as the depth increases. This is to be expected since the amount of material being removed increases with the depth of the cut.

In trying out different kinds of wheels and abrasives on the testing apparatus it was found that more reproducible results could be obtained by using a copper wheel operated in a mixture of levigated alumina. The set up for this test is much the same as shown in Fig. 2 except that the wheel cleaner is omitted and a small pan containing the abrasive mixture is placed under the wheel. The copper wheel is of the same dimensions as the abrasive wheel. This test is used where more accurate results are required. The principal objections to this test are that more time is required and it is rather difficult to control the abrasive mixture, principally because it soon becomes contaminated with particles of chromium.

Other tests which showed some promise were one in which a chromium plated rod was rotated in dry abrasive particles and one in which a small test specimen was held against a rotating abrasive cloth disc. The first method was not satisfactory because the pressure of the abrasive grains on the rod could not be controlled and also because there was no provision for mixing or stirring the abrasive particles. One advantage to the second method was that the apparatus could be easily arranged to measure the amount of work done in removing the chromium. However, this test was not considered practical because it was found necessary to change the abrasive cloth disc frequently in order to secure consistent results. One interesting test which gives some indication of the hardness of chromium plate was made by chromium plating nitrided steel. Samples of nitrided steel ranging in Brinell hardness from 600 to 900 were chromium plated with a plate thickness of 0.005″. A hardness test was then made after chromium plating and it was found in each case that a higher reading was obtained, the increase in the Brinell number of the chromium plated piece over the plain piece decreasing as the hardness of the plain steel increased. The tests were made on a Vickers diamond point machine.

The purpose of these abrasion tests was not to obtain an indication of what a chromium plated part would do in service but was merely to compare different chromium plates in order to improve the quality of the chromium plate. In some few instances it was found that the results obtained on the abrasion testing machine were reproduced in service. This was true, for example, of liners for a dry pressed brick mold. Some attempts were made to compare the abrasion resistance of chromium with that of other metals but the results were so irregular that the tests were considered worthless. However, the testing machine has answered its original purpose—that of comparing the qualities of different chromium plate—quite satisfactorily.

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Dr. Leonard Harrison Cretcher has been appointed to an assistant directorship in the institution. Dr. Cretcher, who, since 1926, has been serving as head of the Institute's Department of Research in Pure Chemistry, is a specialist in organic chemistry and will have supervisory charge of a group of industrial fellowships that are concerned with problems in organo-chemical technology.

CATHODIC PROTECTION

of Metals in Neutral Solutions

By U. R. Evans*

A former article by J. Stockdale and the author[1] discussed cathodic protection in *acid pickling baths.* Cathodic protection is at present more frequently employed in *neutral liquids;* zinc protector bars are still considerably used, while coatings of zinc or aluminum often prevent rusting of iron even where the iron is exposed at cracks or pores in the coat.

The condition for protection is that the cathodic current density on the iron must exceed a certain "protective value." Bauer and Vogel[2] found this value in unstirred sodium chloride of various concentrations to be about 10.6 microamps./cm.^{2} Recent experiments at Cambridge have shown that far higher values are needed if the liquid is stirred. In stagnant solutions, a layer of sodium hydroxide is maintained over the cathode surface; any iron salts oozing through weak places in the invisible primary oxide-film are precipitated in actual contact with the surface, thus automatically sealing the weak points. In stirred solution, this naturally does not occur, and corrosion will continue unless the current density (i.e., the general flow of cations *toward* the iron) is raised sufficiently to counteract this oozing of iron cations outward through the skin. Several experiments have shown that mild steel (H 28) "protected" with a cathodic current density of 45–55 microamps./cm.^{2} in 0.1 M sodium chloride containing potassium ferricyanide is still corroded continuously at the edges if the solution is stirred once a minute, but the attack slows down and finally ceases if the stirring is abandoned. The rate of attack upon rotating specimens of mild steel under various cathodic current densities has been measured in this laboratory by L. C. Bannister; the results, shown in Table 1, indicate that here the low current density recommended by Bauer and Vogel only slightly reduces the attack, which is still serious even at 5 times that current density. Likewise, certain cathodic polarization curves, now being traced for another purpose by S. C. Britton in this laboratory, yield an approximate idea of the protective current density, since the curves show an abrupt change of direction at the current where rusting starts; these indicate that the protective current density in potassium chloride or sulphate solution is not less than 65 microamps./cm.^{2} when the solution is continuously stirred.

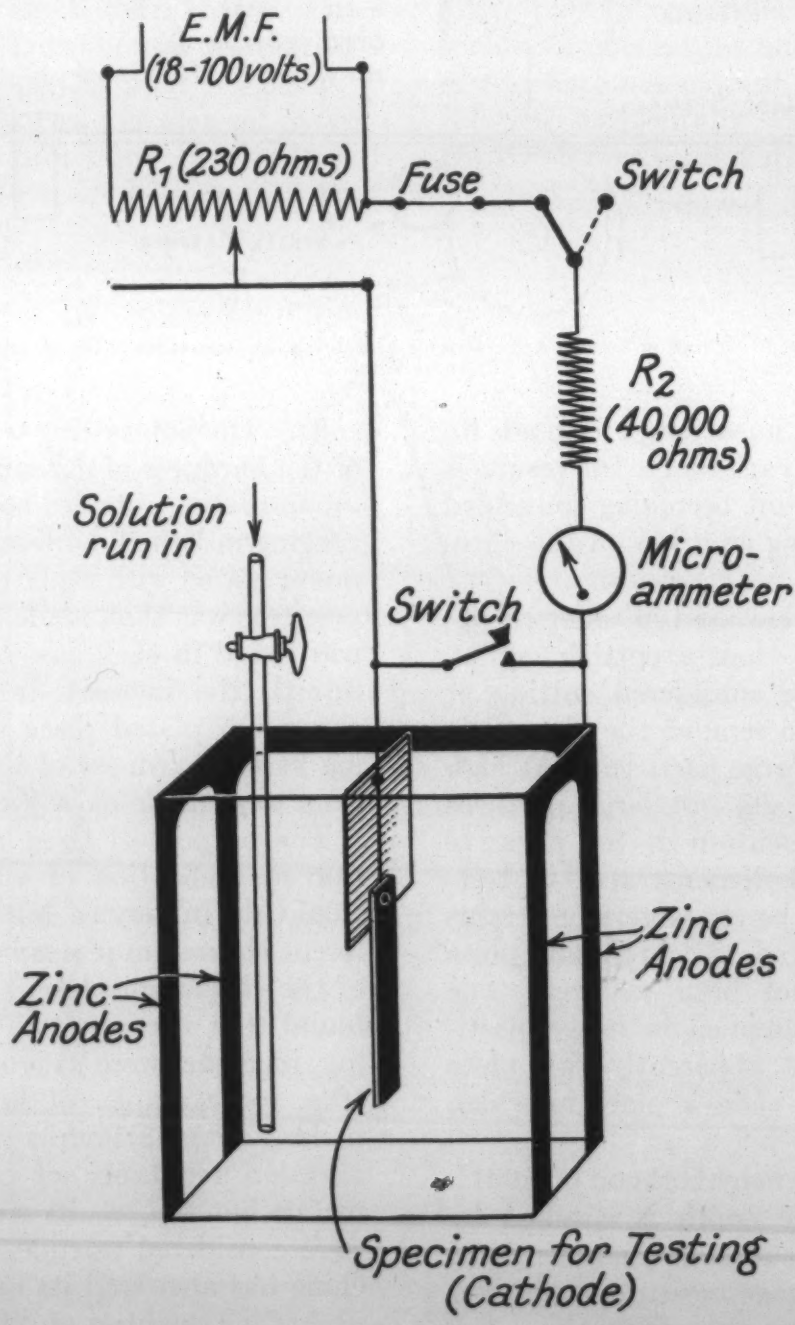

Fig. 1

A feature of the protective current density is that it varies from one specimen to another, even if the material, the solution and the conditions are kept constant. For protection is a "one-event phenomenon," and the so-called "Law of Averages," which gives reproducibility to "many-event phenomena," does not operate here. This question of reproducibility in corrosion work has been discussed by the author elsewhere,[3] but the following considerations may make the matter clearer. A sheet of steel is covered with a primary oxide film invisible while in contact with the bright metal, although visible when removed;[4] this film has numerous weak points, a few being "extremely weak," whilst others are less important. When the sheet is cut up into small specimens, only a few of these specimens will contain the "very weak" points; such specimens will require a greater current density to stop oozing than the specimens containing points of normal or sub-normal weakness.

Evidently what is required is a rapid method of determining the protective value, which, even if somewhat rough, will enable a large number of specimens to be tested, so that the average can be taken. Such a method has been worked out, the principle

* Cambridge, England.

[1] *Metals & Alloys*, Vol. 1 (1930) page 377.

[2] *Mitteilungen Königliches Materialprüfungsamt*, Vol. 36 (1918) page 114.

[3] *Transactions, American Electrochemical Society*, Vol. 57 (1930) page 407.

[4] For details see *Journal Chemical Society* (1927) page 1020; (1929) pages 92, 2651; (1930) pages 478, 1361, 1773.

Table 1—Corrosion under Conditions of Cathodic Polarization

(*L. C. Bannister*)

Material, Steel H28. Liquid, M potassium chloride. Immersed area (each side), 3.0 × 3.0 cm. Time, 1.5 hours. Speed of rotation, 28 revolutions/minute.

Current-Density (Microamps./cm.²)	Weight-loss (Mg./hr.)
0	0.0488
0.8	0.0436
1.9	0.0418
10.0	0.0383
30.0	0.0175
50.0	0.0078
55.0	0.0017

being shown in Fig. 1. An adjustable E. M. F. applied through a resistance (40,000 ohms) high compared to the resistance of the experimental cell, allows a constant small current to pass between the zinc anodes and the iron specimen to be studied. The liquid, containing 0.1% potassium ferricyanide as indicator, is run in, 2 cc. each 15 sec., from a burette; thus the area covered is gradually increased, and the current density gradually decreased; when the current density passes below the protective value, blue points appear at the edges of the specimen. If the specimen is coarsely abraded just before the experiment, the blue spots appear on the face instead of the edges, but the current needed for protection is not increased; (if anything, it is diminished). Special series of experiments showed that, on the average, the results are not altered if 1 minute—instead of 15 sec.—is allowed between each addition.

The results are shown in Table 2, and the analysis of materials used in Table 3. The "Normal" preparation of the surface consisted in abrasion with French Emery No. 1 and degreasing with carbon tetrachloride. The remarkable variation between individual specimens in the same solution is well brought out in Table 2. The nature and concentration of the solution has very little effect; certainly the change from one salt to another has far less effect than the change from one specimen to another. A few experiments in M/10 sulphuric acid, however, showed continuous corrosion at a current density of 5000 microamps./cm.², a value far higher than any shown in Table 2. This

Table 3.—Analysis of Materials

	C	Mn	Si	S	P
Mild Steel sheet H28 (0.32 mm. thick)	0.26	0.57	0.15	0.014	0.018
Pure Iron sheet G1 (0.20 mm. thick)	0.02	0.01	0.01	0.017	Trace
Circular Steel Rod SR1 (11 mm. diameter)	1.195	0.286	0.202	0.009	0.021

acid destroys the primary skin, as shown in previous work.[5] Saturated carbonic acid, which does not destroy the skin, seems to allow protection at a current density not unlike that given by neutral salts, but the end-point is very indefinite. Calcium bicarbonate in saturated solution appears to allow protection at current densities lower than those needed with the other salts, but here also it is impossible to be sure of the true value; probably calcium carbonate is deposited on the cathode, and serves as precipitant for oozing iron salts, thus complicating the phenomena. Numerous experiments were made in solutions containing (in addition to chloride, sulphate or nitrate) various amounts of potassium chromate, sufficient enormously to reduce the area attacked under conditions of "free corrosion" (i. e., immersion without cathodic protection); these indicated that the value of the current density needed for complete protection was not reduced by chromate within the range of concentration studied (this range was limited by difficulty with the end-point).

Differences in the composition or form of material make less difference to the protective value than was anticipated, although the high-carbon steel rod requires a greater current for protection than the pure iron sheet. In the case of sheet, the time-interval between the cutting of the specimen and the experiment has remarkably little effect. The most surprising result is that the cutting of a screw-thread on the rod tends to reduce rather than to increase the current needed for protection; since the screw-thread doubles the area, the *true* current density needed for protection of the threaded rod is really less than one-third of that needed on the smooth rod. The probable

[5] *Journal Chemical Society* (1930) page 478.

Table 2.—Values for Current Density below Which Production Fails

Temperature 15° C. ± 0.5°

Material	Surface Preparation	Time of Storage before Testing	Solution	Limiting Current Density of Individual Specimens (No Allowance for Edge or Screw-Thread), Microamps./cm.²	Average Limiting Current Density, Microamps./cm.²
Steel H 28	Normal	3.5 hours	0.1 M NaCl	84, 152, 144, 151, 202	147
Steel H 28	Normal	36 days	0.1 M NaCl	179, 114, 131, 157, 178	152
Steel H 28	Normal	2.5 hours	0.1 M KCl	151, 136, 87, 130, 231	147
Steel H 28	Normal	23 hours	0.1 M KCl	135, 158, 91, 120, 174	136
Steel H 28	Normal	4 days	0.1 M KCl	93, 110, 141, 174, 100, 95, 91, 66, 69, 87	102
Steel H 28	Normal	13 days	0.1 M KCl	135, 146, 127, 201, 207, 135, 130, 164, 156, 156	156
Steel H 28	Normal	32 days	0.1 M KCl	131, 175, 151, 112, 117	137
Steel H 28	Normal	32 days	Cambridge tap-water	115, 105, 102, 139, 105	113
Steel H 28	Normal	32 days	0.1 M $MgSO_4$	123, 127, 130, 117, 107	121
Steel H 28	Normal	4 days	0.1 M $MgSO_4$	66, 105, 87, 100, 101	92
Steel H 28	Normal	16 hours	1.0 M KCl	83, 93, 98, 61	84
Steel H 28	Normal	16 hours	0.1 M KCl	79, 116, 92, 111, 124	104
Steel H 28	Normal	16 hours	0.1 M K_2SO_4	68, 94, 165, 138, 152	123
Steel H 28	Normal	16 hours	0.1 M KNO_3	133, 78, 108, 98, 124	108
Iron G 1	Normal	24 hours	0.1 M KCl	91, 135, 123, 102, 105, 91, 112, 68, 83, 58, 55	93
Iron G 1	Normal	2 days	0.1 M KCl	63, 74, 148	95
Iron G 1	Coarsely abraded just before experiment (No CCl_4 washing)	(2 days between cutting and experiment)	0.1 M KCl	69, 63, 105, 81, 70	78
Rod SR 1	Smooth surface as received (sharp edge at bottom covered with vaseline)	.....	0.1 M KCl	137,* 192, 120, 102, 161*	142
Rod SR 1	Screw thread cut†	1 day after screw cutting	0.1 M KCl	85, 75, 81, 77, 84	80

* The attack starts in these cases at the edge of the vaseline-covered area.
† Screw thread roughly doubles the surface area.

explanation is that the grooves retain sodium hydroxide, while the ridges between the grooves, where there is no special retention of alkali, actually receive a greater current density than a plain surface would receive.

No doubt the current density recommended by Bauer and Vogel would be sufficient for stagnant liquid. Where the liquid is likely to be in motion, a higher value is necessary. It would seem that at least 250 microamps./cm.^{2} is called for; this is equivalent to 2.5 amps./m.^{2}, or 0.23 amps./ft.^{2}

It is remarkable how complete is the protection, provided that the current density is sufficient. Some experiments made by the author[6] in 1928 showed that steel to which a zinc strip was strapped remained quite unrusted after 40 days immersion in liquids, which began within a few minutes to attack similar steel specimens not in contact with zinc. But the protection is "sacrificial." Zinc is attacked in the place of the steel, and the protection will cease when the zinc is used up; moreover, unless the liquid is sufficiently corrosive to attack the zinc at a rate calculated to give the "protective current density" on the steel, rusting may occur. This explains the strange fact that relatively non-corrosive waters may sometimes cause rusting of "protected" iron and steel, while more corrosive waters will not. Good examples were observed in the study of steel covered with cracked coatings of zinc and aluminum. In salt waters, either metal prevents rusting at the cracks, even though the steel basis was there exposed; the protection usually persists longer in the case of aluminum coats, since that metal is consumed less rapidly than zinc. But in many fresh waters, which are less corrosive, only zinc prevents rusting at cracks in the coat; in such waters, aluminum is attacked too slowly to give the necessary protective current density on the steel where it is exposed. Hence a broken coat of aluminum will prevent rusting in the highly corrosive salt water, but allow rusting in the less corrosive fresh water—a fact which the author has noticed with aluminum coatings obtained by more than one commercial method.[7] When quite unbroken, aluminum coatings give excellent protection in fresh water; and whether broken or not they are preferable to zinc coatings for use in salt water, since the coatings themselves will survive much longer; but they are not suitable for use in fresh water if there is any risk of cracking.

Another instructive example of cathodic protection has been noted by S. C. Britton in the outdoor paint tests now proceeding at Cambridge. Plates of steel were coated with a paint containing zinc dust (36 g.) and raw linseed oil (10 cc.), but narrow strips were left unpainted; when the bare strip was narrow (1.5 mm.) the specimens could be exposed to the atmosphere for 10 weeks before rust began to appear on the bare steel, since the metallic zinc gave it cathodic protection; when, however, the bare strip was 7 mm. wide, rust appeared after the first rain-shower. This temporary protection at small gaps in coats of metallic zinc paint can be observed on scale-covered metal as well as on descaled steel.

[6] *Journal Society Chemical Industry*, Vol. 47 (1928) page 73T.
[7] *Journal Institute of Metals*, Vol. 40 (1928) page 99; *Journal Electroplaters & Depositers Technical Society*, Vol. 4 (1929) page 69.

Technical Control in an Industrial Plant[1]

By R. E. Christin[2]

According to Webster the word "Control" means among other things, a regulation or a governing, in this case, of materials, operations, etc., to avoid unnecessary expense or steps. It is such regulation by an individual or department with the object of reducing costs that I wish to stress.

We all know that theory holds an important place in industry and that practice follows. The idea must first come before the act or else the course is a haphazard one. But proper bodies must carry out the theory and convert it into practice in order to reach a definite and profitable ending.

A strong arm of a good organization—one which will stand keen competition and survive—is technical control or regulation within the walls of an industrial plant.

In the steel industry, for instance, from the mining of the ore to the final inspection of the finished product, whether automobile, safety pin or micrometer, each operation and each bit of material used, should have technical control in order to obtain good results. Rejections do not have to be tolerated to any great degree. When a heat of steel is not according to analysis, someone has failed to regulate some element or some operation. And when steel of different analyses is mixed together under one nomenclature, someone has failed in his duties. Then technical control is necessary to prevent loss of labor, and loss of material and loss of time. Whereas, if the control had been inserted at the proper location, much expense would have been avoided and good-will would not have been lost.

By mere insertion of technical control, it is not a positive conclusion that *all* wrongs would be eliminated. There is no form of control which will eliminate errors of human equation 100%. By proper method of attack of the problem at the source of ailment, control is made apparent.

When we speak of technical control in an industrial plant, we have in mind the prevention of bad work, the elimination of work only good enough to get by. A study of the problems by one possessed of knowledge of materials and their characteristics will go a long way to aid in curing the trouble as well as eliminating their recurrence.

In the writer's opinion, the difference between the efficiencies of present industrial plants as compared with those of 20 years ago is due to a great extent to technical control of the various materials by specifications and correct applications, such as chemical analysis, checking for various defects in raw materials, heat treatment, control of pickling baths, frequent checking of plating solutions, quick tests for physical properties, proper inspection, etc.

It is all important that an analysis of the problem to be solved, must be made with good judgment. One must be careful beforehand not to enter into long tedious and complicated processes which are apt to hinder production. The methods to be followed must be so arranged as to obtain results quickly and efficiently. There is not always time for thorough research into the question or problem. One must use the means at hand until our research brothers can uncover other means. It is not sufficient to place the blame of trouble on the source of supply. One must insert corrective measures in such instances, which will yield productive results, rather than let the trouble of correction or segregation fall back to the source of supply or to the manufacturer of the raw materials used in fabrication. And when one department discovers a flaw or an error made by another department of the same plant, it is the technical controller, who is called upon to correct the mistake or offer a remedy for prevention.

No machine, no matter how automatic it might be made, is capable of producing efficiently and economically without human control, and no industry should be expected or should expect to produce efficiently and economically against keen competition without a technical controller possessed with knowledge of the materials and operations in the plant, their treatment and their use as well as their abuses so that corrective measures can be inserted when needed.

[1] Dinner talk before Columbus Chapter, American Society for Steel Treating, Dec. 9th, 1930.
[2] Metallurgist, Columbus Bolt Works Co., Columbus, Ohio.

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P. N. Guthrie, Jr., was elected to the presidency of the Reading Iron Company. He assumes his duties immediately with offices at the headquarters of the company, Baer Building, Reading, Pennsylvania.

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The Fuller Lehigh Company, a subsidiary of The Babcock & Wilcox Company, will move its manufacturing operations and offices from Fullerton, Pa., to Barberton, Ohio. The executive offices will be located at 85 Liberty Street, New York.

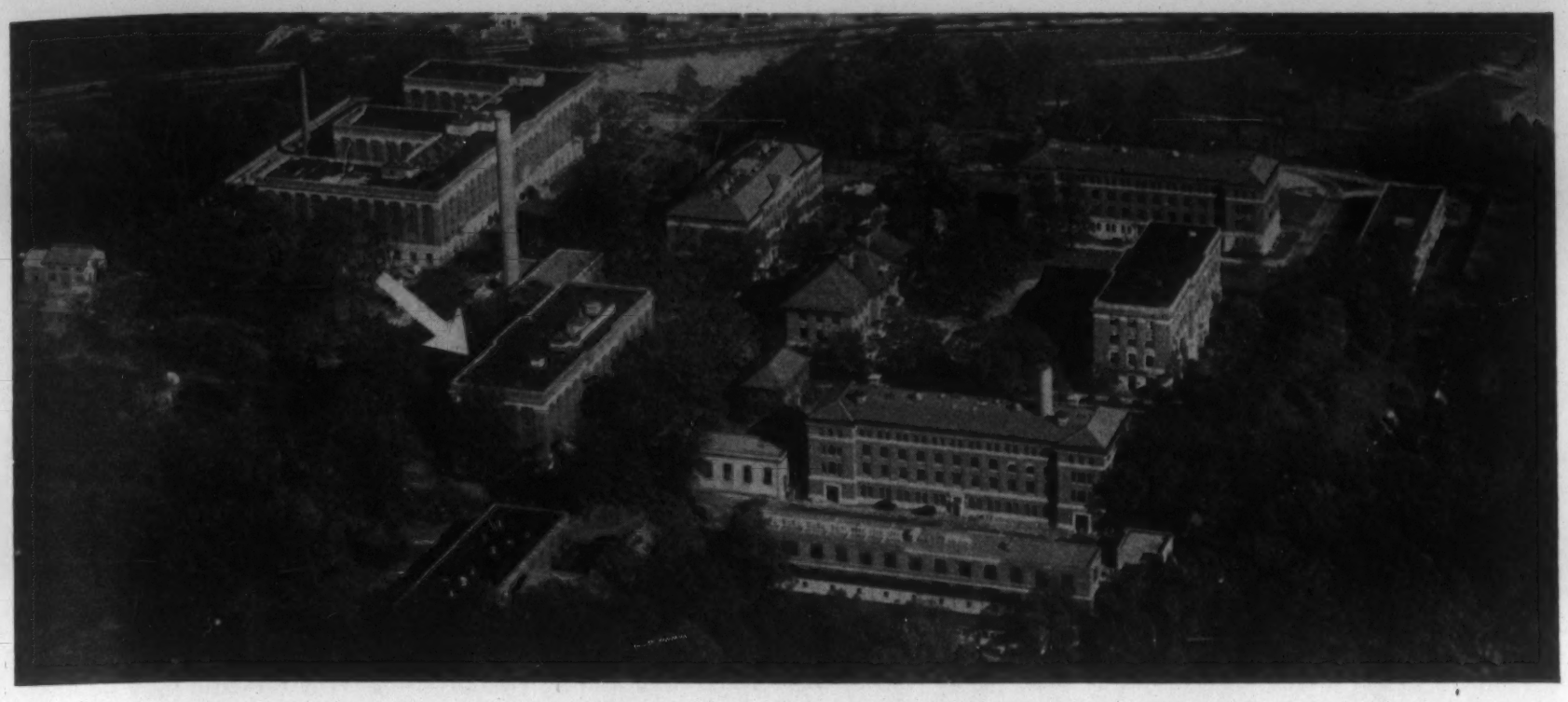


Fig. 1.—Aerial View of the National Bureau of Standards; the Division of Metallurgy Is Housed in the Building Indicated by the Arrow

What the **Bureau of Standards** Does for **Metallurgy** *

By Richard Rimbach

EXPERIMENTAL work on metals within the United States Department of Commerce is divided between the Bureau of Mines and the Bureau of Standards. Work on metals is, of course, carried on in some of the other bureaus of the Department, for example, the Bureau of Foreign and Domestic Commerce. Such work, however, is not as a rule immediately dependent upon laboratory investigations. There is practically no overlapping in the metallurgical work of the Bureau of Mines and the Bureau of Standards, the rather clearly defined line of demarcation between the fields of activity being such as would be inferred from the names of the two bureaus. Problems relating to mining, and to such aspects of "process" metallurgy as ore dressing, ore concentration, leaching and precipitation, smelting and the like naturally fall within the field of activity of the Bureau of Mines. A great deal of the metallurgical work of the Bureau of Standards is of the character connoted by the term "physical metallurgy." In addition to investigative work, the Bureau is called upon to act as a testing laboratory for practically all of the other government departments. Most of the metallurgical

* Publication approved by the Director of the Bureau of Standards.

Fig. 2.—View in the Experimental Foundry for Non-Ferrous Castings

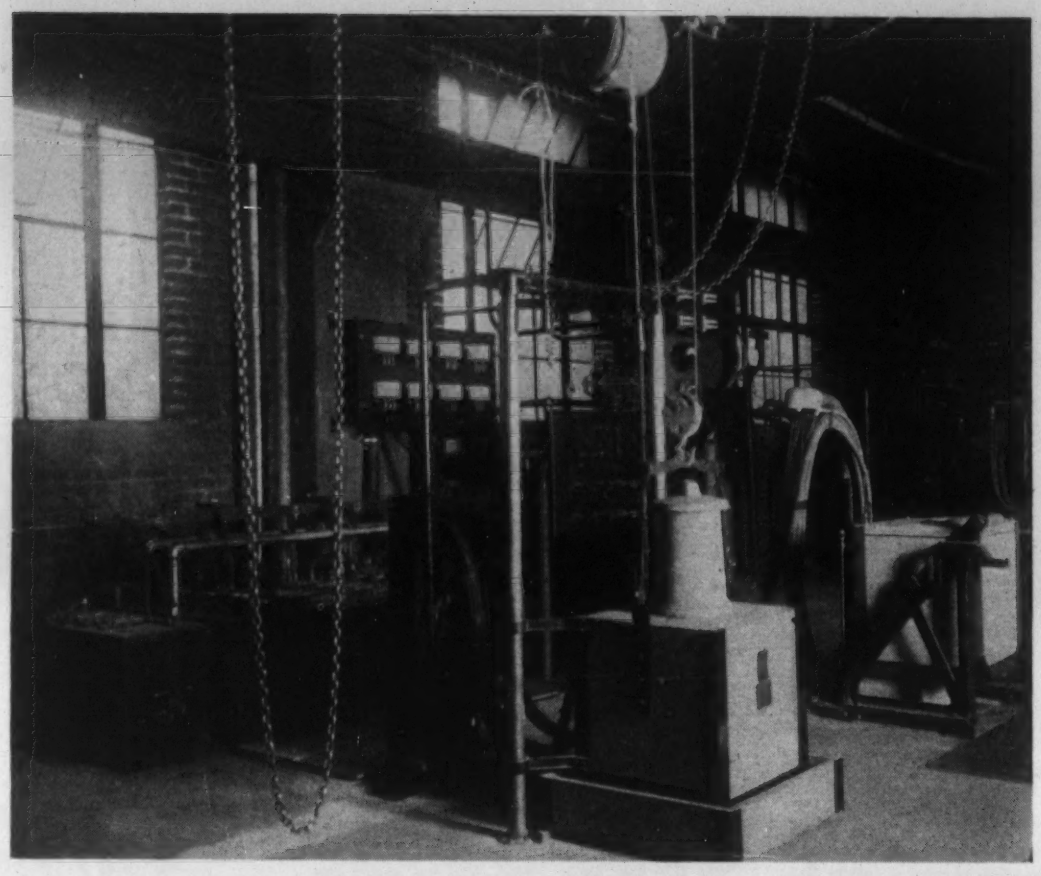


Fig. 3.—High-Frequency Induction Electric Furnaces for the Melting of Metals in Large Quantities. The One at the Left Is of the "Lift-Coil" Type. The Electric Hoist Shown Aids Greatly in Handling the Metal Quickly and Efficiently upon Pouring

tests received from these sources are of the nature of minor research problems, however, rather than simple routine tests.

The Division of Metallurgy of the Bureau of Standards is housed in the building indicated in Fig. 1. From the location of this building with respect to the others of the group which constitute the Bureau, it is usually referred to as the Northwest Building. It is of reinforced concrete construction faced with brick and limestone, covers a ground area of 200 by 65 feet and consists of four stories. The two lower stories are devoted to metallurgy, and preparations are now underway for using much of the third floor for metallurgical work now housed elsewhere.

The general purpose of the work of the Division of Metallurgy is best indicated by the term, "standards of quality." All investigative work undertaken is initiated and directed with the general aim in view of the establishment of standards of quality. In addition to above mentioned tests, a great deal of investigative work is undertaken at the specific request of various government departments and much coöperative work with the various national technical societies is carried out.

For convenience, especially for administrative purposes, the Division of Metallurgy is divided into sections dealing with the predominating aspects of metallurgical work and to some extent, the methods of investigation, such as the melting and casting of metals, the mechanical working of metals, thermal treatment, etc. The following description of the laboratories is based on the division of the work into these sections. The illustrations used have been chosen to represent some of the current phases of the work rather than as a general description of the various laboratories.

MELTING AND CASTING OF METALS

A large portion of the ground floor is devoted to the experimental foundry, a view of part of which is shown in Fig. 2. Although experimental in the sense that the main purpose is the study of metallurgical problems connected with the casting of metals, the foundry is also practical in that all of the castings required by the Bureau's instrument shops as well as those for some of the other government departments are made here. The study of foundry sands for molding and cores has received much attention, and in coöperation with the American Foundrymen's Association the testing and control of sands has been put on a logical basis. Equipment employed at the Bureau for two of the tests for molding sands—the determination of compressive strength and the sintering temperature, were illustrated in a previous issue[1] of METALS & ALLOYS. Of the various furnaces used for melting may be mentioned two high-frequency induction furnaces, the installation of which has just been completed, which are shown in Fig. 3. One of these having a capacity, with the present set-up, for producing melts of somewhat over 200 pounds (steel), is arranged for tilting for pouring the metal; the other is of the lift-coil type. The study of the properties of copper-base cast alloys now underway in coöperation with the Non-Ferrous Ingot Metals Association will be greatly expedited by the use of this equipment, as will also the development of the method for measuring the shrinkage of cast iron, a problem now under study in coöperation with the American Foundry-

[1] Vol. 1, May 1930, page 496.

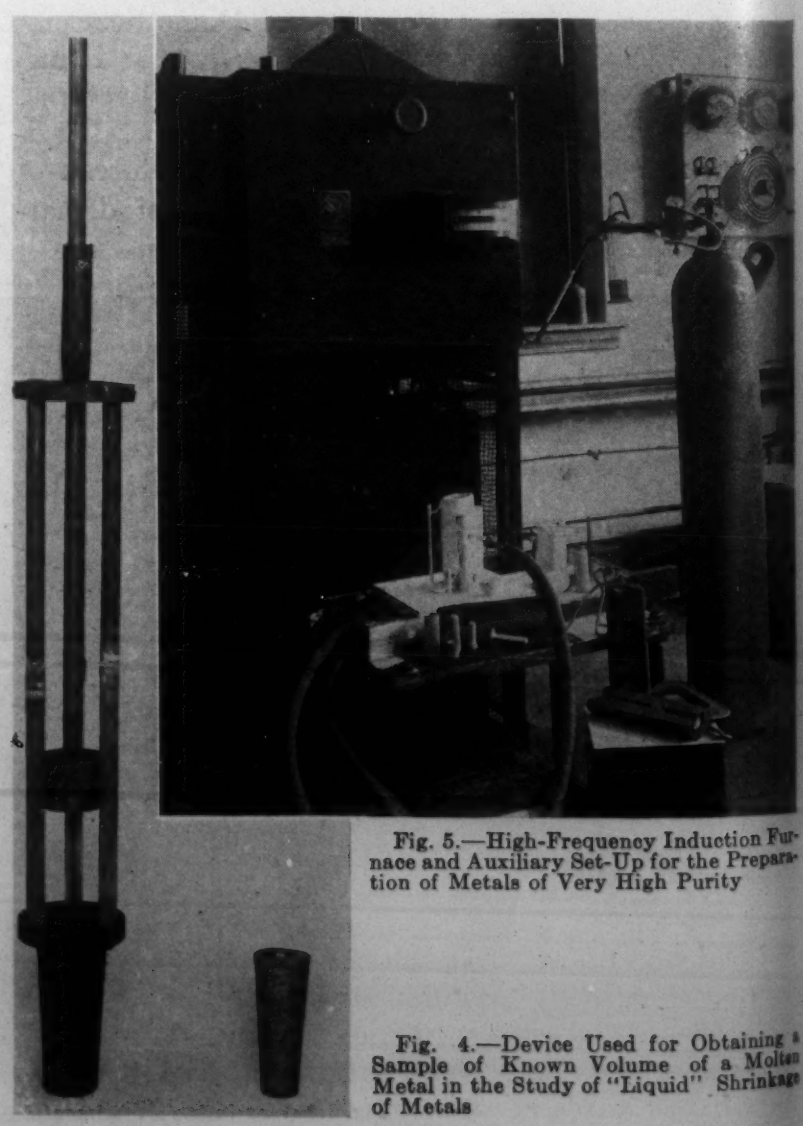


Fig. 5.—High-Frequency Induction Furnace and Auxiliary Set-Up for the Preparation of Metals of Very High Purity

Fig. 4.—Device Used for Obtaining a Sample of Known Volume of a Molten Metal in the Study of "Liquid" Shrinkage of Metals

men's Association. Some of the equipment used in the latter work is shown in Fig. 4. Other equipment for melting metals, in addition to the usual type of crucible furnaces for melting by both oil and gas heating, includes an electric arc furnace (indirect heating) of the rocking type and a small cupola capable of delivering 1/2 ton of cast iron per hour.

CHEMICAL METALLURGY

There are many phases of the problem of molten metals which cannot be studied by ordinary foundry methods. In the section of chemical metallurgy are studied those problems relating to composition as determined by conditions of melting which have an important bearing on the properties of the metal. One of the foremost of these is that of "gases in metals," a term used in reference to the compounds resulting from oxygen, nitrogen, etc., within the sound metal rather than the gas contained within cavities in the metal. The preparation of metals of a very high degree of purity and the preparation of such metals in suitable form so that the fundamental characteristic properties can be determined is also of importance. The set-up used for this, the essential part of which is the high frequency induction furnace, is shown in Fig. 5. The preparation of suitable refractories which will withstand heating at the high temperatures often necessary, without contaminating the metal under preparation is a necessary adjunct of this work. The mechanical working of very pure metals and precious metals is as a rule carried out in the section of chemical metallurgy as the question of maintenance of purity of the material is of paramount importance. For this reason swaging equipment (Fig. 6) used largely on very pure metals and platinum group metals and sapphire dies and sintered tungsten carbide dies for both cold and hot drawing of wires are in charge of the chemical metallurgy section.

Fig. 7.—16-inch Rolling Mill for Sheets and Rods

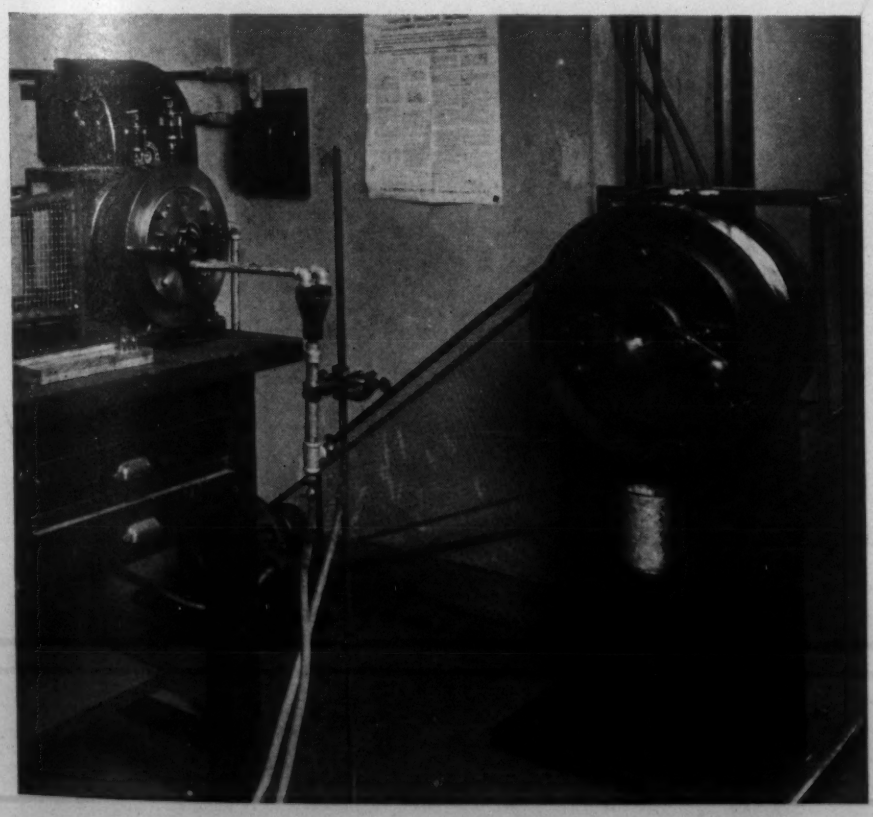


Fig. 6.—Swaging Machines Used in the Mechanical Working of Metals. Both Hot and Cold Swaging Can Be Done

MECHANICAL WORKING OF METALS

The ability to respond to mechanical working determines in very large measure the usefulness of any metal. Equipment used in the rolling of metals is shown in Figs. 7 and 8. The larger mill, with 19-inch rolls is driven by a 150 H.P. motor with adjustable speed which permits operation of the rolls for hot and cold work. Grooved rolls for rods are also provided. The smaller mill, with 5-inch rolls, is better adapted to studying some of the theoretical aspects of metal rolling than is the larger mill. In addition to the rolling mills shown the Bureau is equipped with a forging press of 150 tons capacity, operated by compressed air, and a draw bench of the endless-chain type designed to give a pull of 20,000 lbs. Small hand and motor-driven rolls, 2-inches in diameter, for preparing strip and rod which may then be drawn into wire, are also available.

The apparatus available for determining the mechanical properties of metals, for measuring the effect of mechanical working, heat treatment, or structural changes in general, includes three tension machines, two of the lever type (10,000 and 100,000 lbs. capacity), and one of the hydraulic-type (50,000 lbs. capacity), the last having auxiliary attachments designed to permit the maintaining of constant loading over a long period of time. Machines available for determining the endurance properties of metals are of the rotating-beam type and the axial-loading type.[2] A special adap-

[2] Illustrated in *Metals & Alloys*, Vol. 2, Feb. 1931, page, 77.

tation of the rotating-beam machine for determining the endurance properties of a relatively long span of wire without any preliminary reduction of the cross-sectional area of the wire. Various types of extensometers including an optical load-extension recorder permit the study of the stress-strain relationship of a metal throughout the entire range from no load to failure. In addition to the instruments in common use for determining hardness a small dead-weight machine of the Brinell type making use of a $^1/_{16}$-inch ball is available.

A number of machines of different basic design are available for determining the resistance of metals to wear. The one designed to simulate the wear which a plug gage encounters in service is illustrated in this issue.[3] Another type depends on the friction between two metal discs which are made to roll against each other along their peripheries, with or without lubricants, with a 10% difference in peripheral speed. The abrasive effect of sand used as a stream flowing between the test specimen and the edge of a revolving metal disc or as a sand-blast, form the basis of other types of tests employed. The study of resistance to wear as, for example, in the study of bearing metals, must be accompanied by other tests preferably carried out at service temperatures such as resistance to impact and repeated pounding, etc.

The general problem of the machinability of metals and the cutting of metals requires regular shop installations.[4]

places the use of the chronograph and standard clock is shown in Fig. 10. The thermal behavior of metals during sudden cooling (quenching) is studied by means of the apparatus shown in Fig. 11—the essential part of which is the "string" galvanometer or electrocardiograph. By the use of samples of known characteristics, the apparatus can be used for studying the properties of the various liquid media used in quenching as "coolants."

Another important phase of thermal metallurgy is the study of the "high-temperature tensile properties" of metals. This involves the determination of the creep of metals maintained for a long period of time under constant load at an elevated temperature, the equipment was illustrated in the December 1930 issue of METALS & ALLOYS,[5] and the so-called short-time tension test at high temperature in which a ten-

[5] Page 882.

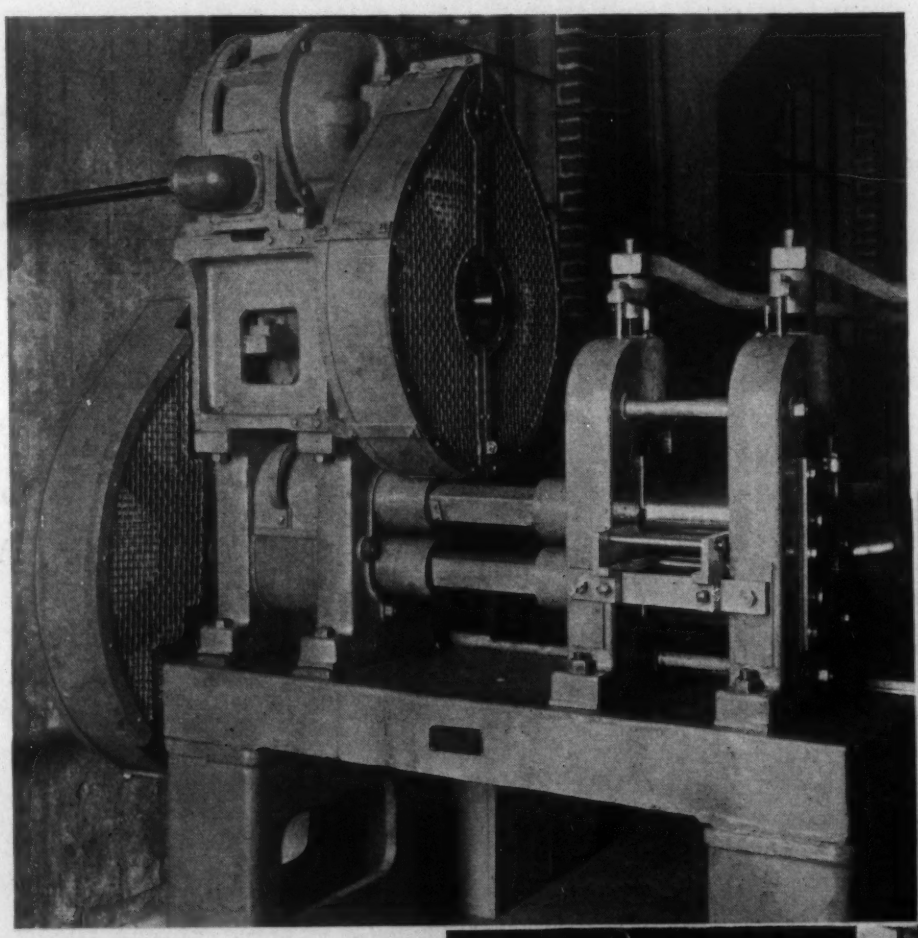


Fig. 8.—5-Inch Rolling Mill

Fig. 9.—Equipment for Thermal Analysis of Metals. (a) Modified Rosenhain (Differentially Heated) Tubular Electrical Resistance Furnace and Mercury Diffusion Vacuum Pump

THERMAL METALLURGY

A knowledge of the behavior of metals with respect to phase or other changes at elevated temperatures is of fundamental importance to the metallurgist. Equipment available for work of this kind includes a modification of the Rosenhain method for heating a sample at a known and controllable rate by moving it mechanically together with the evacuated tube in which it is enclosed, from the cooler to the hotter end of an electrically heated tubular furnace (Fig. 9) and vice versa for cooling. The necessary auxiliary equipment includes a mercury diffusion vacuum pump, a galvanometer, precision potentiometer, and chronograph with connection to the Bureau's standard clock. A specially designed recorder for the automatic recording of the inverse-rate thermal curve which re-

[3] Page 54.

[4] Machinability and Tool Life, by T. G. Digges, page 44, this issue.

sion test is carried out in the usual manner on a specimen maintained at the desired temperature, the most important feature of the test being the determination of the stress at which the material ceases to behave electrically. The Tuckerman modification of the Martens extensometer, as developed at the Bureau, is used for this.

Equipment of the usual types such as electrical furnaces, lead and salt baths, cyaniding, carburizing and nitriding equipment is available for experimental heat treatment of steels, duralumin, and other nonferrous alloys.

STRUCTURE OF METALS

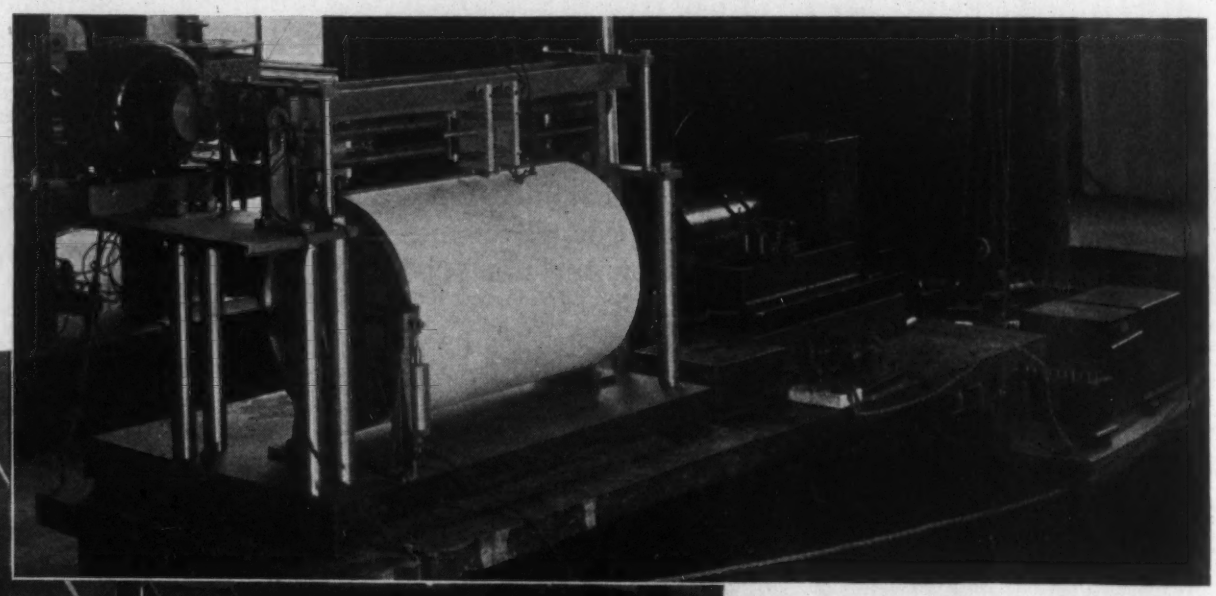
For the examination of the structure of metals, there are available a number of large metallographic microscopes. A large microtome is used for surfacing the softer materials which can be polished only with difficulty by the usual metallographic methods. A recent development within the Bureau is the automatic polishing machine described in detail in the November 1929 issue of METALS & ALLOYS.[6]

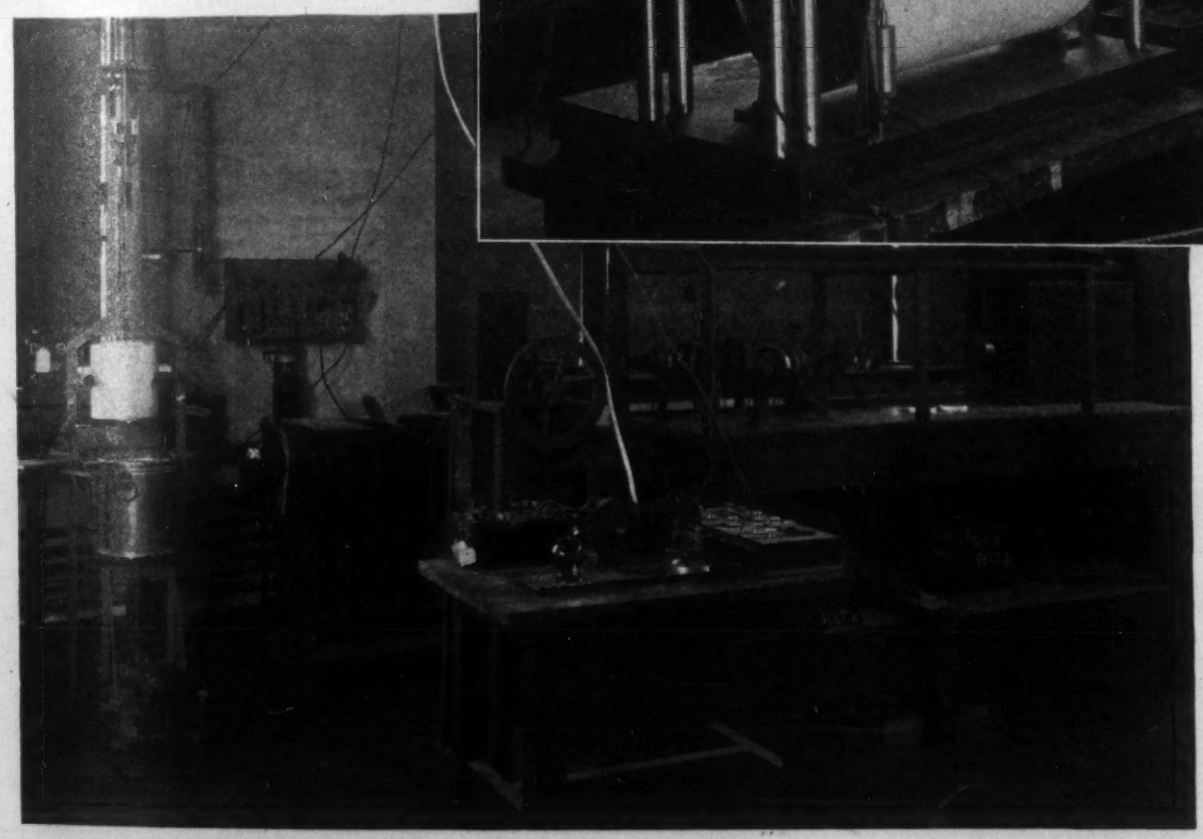
For extending the study of the structure of metals beyond the range of the microscope ample X-ray equipment is available. A variation from the usual X-ray method now under study consists in utilizing the secondary or corpuscular radiation originating from a metal target placed in an X-ray beam.

[6] November 1929, page 226.

Fig. 10.—Equipment for Thermal Analysis of Metals. (b) Automatic Curve-Plotting Device with Potentiometer and Galvanometer in the Background

Fig. 11.—Assembly Used in the Study of the Quenching of Metals. The "String" Galvanometer, the Auxiliary Photographic Equipment and the Furnace with Means for Releasing the Heated Specimen into the Quenching Bath Which Is Gently Agitated by Means of the Rotating Table Constitute the Essential Parts of the Equipment





CORROSION RESISTANCE OF METALS

As an adjunct to structural metallography much work has been done on the corrosion behavior of metals in relation to their structural features particularly with respect to intercrystalline attack. In Fig. 12 is shown the set-up used in this phase of the study of the corrosion of sheet duralumin and other light-metal alloys. The method consists essentially in corrosion, by intermittent immersion, of full-size tension bars the tensile properties of which, after corrosion, are determined and also the changes in their structure. The machine for corroding similar specimens while they were subjected to repeated flexural stressing is shown in Fig. 11 of the Feb. 1931 issue of METALS & ALLOYS.[7] The determination of the behavior of the same material under various exposure conditions is, of course, a vital part of such work. Fig. 13 shows one such exposure-test rack which is maintained at Coco Solo (Canal Zone) through the coöperation of the Bureau of Aeronautics, Navy Department.

The development of suitable methods for determining the corrosion-behavior of a metal under various conditions is necessarily an important part of any corrosion study. Considerable attention is devoted to this kind of work. The apparatus for the study of the "aeration" factor in submerged corrosion, is shown in Fig. 14. The essential feature in the construction of this is the fact that no metal other than that under observation must come in contact with the solution used. Hard rubber and glass are used throughout.

Of the various other kinds of corrosion tests under study may be mentioned the accelerated weathering test for zinc coated materials in which the specimens are subjected to repeated cyclic changes with respect to the corrosive conditions. Each cycle consists of (*a*) exposure to a warm moist corrosive atmosphere (containing SO_2 and CO_2), (*b*) thorough washing by hard vigorous spray, and (*c*) complete drying.

[7] Page 75.

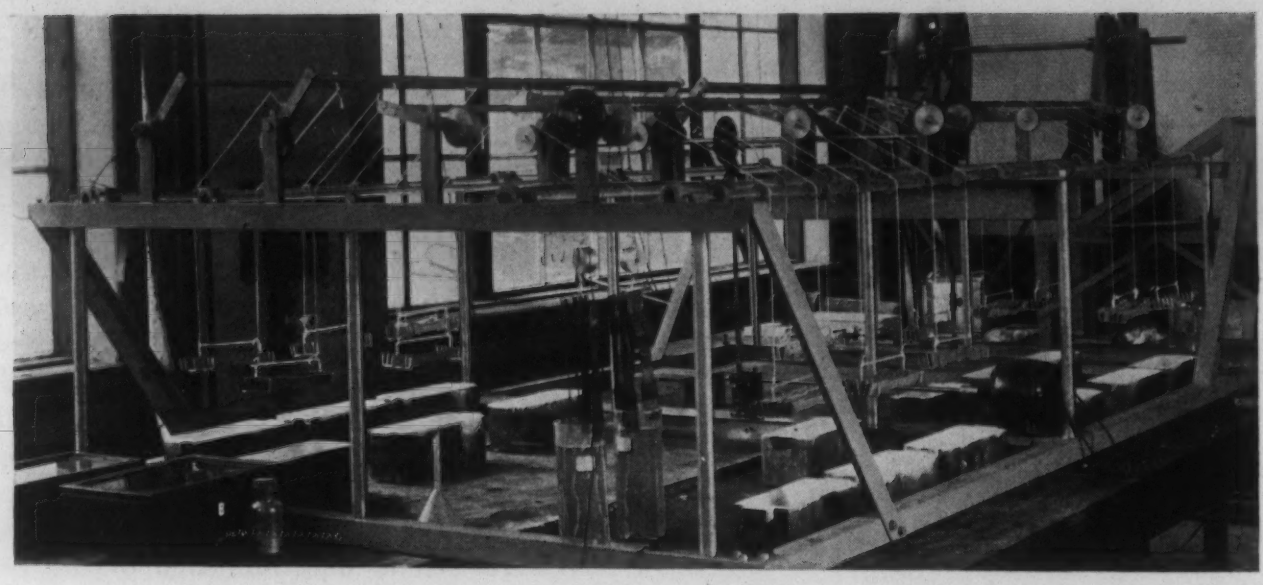


Fig. 12.—Set-up Used for the Corrosion of Metals by Intermittent Immersion or the Wet-and-Dry Method. The Full Size Tension Bars Used As Specimens Are Tested in Tension after Corrosion

MISCELLANEOUS METALLURGICAL STUDIES

An important activity of the Metallurgical Division which is not based directly upon experimental work is the preparation of circulars of information dealing with different metals and their related alloys. The aim of such circulars is to give a rather complete summary of existing information, as given in the technical literature, for each of the important commercial metals.

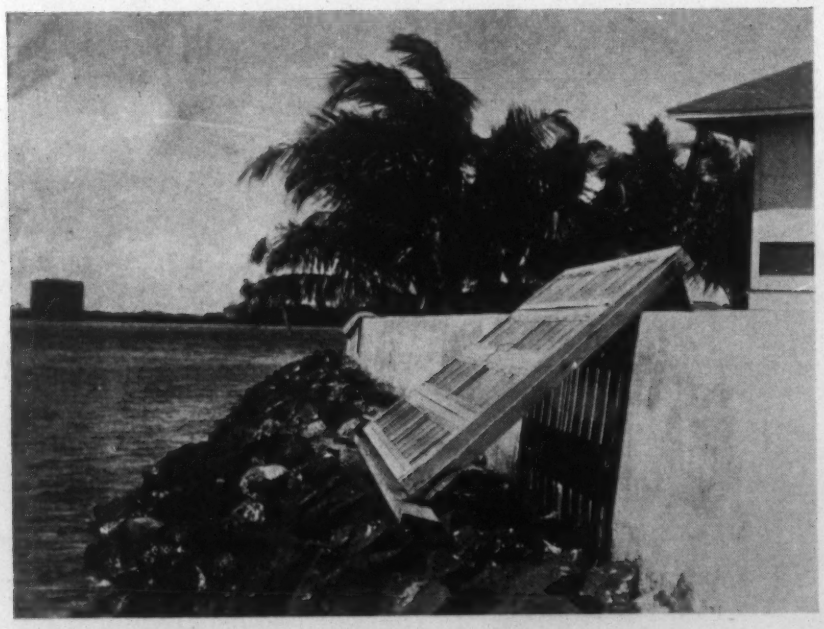


Fig. 13.—Rack for Exposure Tests of Aluminum and Other Alloys. This Exposure Test at Coco Solo, Canal Zone, Is One of Three in Widely Different Climatic Conditions Used to Supplement Laboratory Tests

Researches of metallurgical interest within the Bureau of Standards are not limited to the Metallurgical Division. Determination of the fundamental constants of metals, such as density, electrical resistivity, thermal expansion and thermal conductivity, is made in the appropriate section of the Bureau specializing in such work, and in addition a number of metallurgical studies intimately related to some fundamental property of metals are underway. Typical researches of this kind are the study of dental alloys (closely related to thermal expansion), soil corrosion (related to electrolysis) and protective metallic coating (related to electrodeposition of metals). Much investigative work and testing is carried out in the Engineering Mechanics Section which is distinctly of metallurgical interest. A few typical examples of which mention may be made are the testing of assembled bridge members, duralumin airship girders, welded steel tubing, and airplane parts assembled by welding.

An important phase of the Bureau's work originating entirely in requests received from industry is carried out under the research-associate plan. Under this plan the facilities and equipment of the Bureau are made available to technical and industrial organizations for the study of problems of mutual interest to the industry and to the Bureau, the investigator in each case is supported by the coöperating organization. A number of current metallurgical studies are being carried out under this plan. Among these are foundry problems covering the shrinkage of cast iron and the properties and classification of copper-base non-ferrous ingot metals; the study of alloy steels for high temperatures, the resistance of bearing bronzes to wear and special studies of copper for roofing.

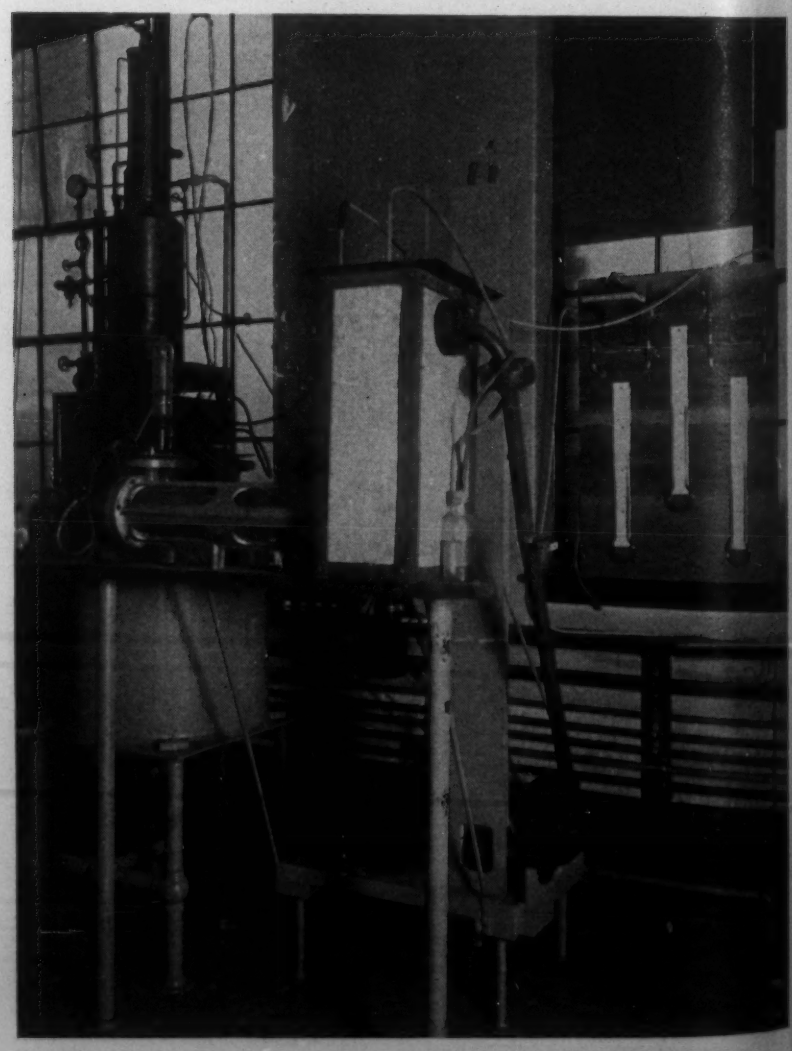


Fig. 14.—Set-Up Used in the Study of the Aeration Factor in "Submerged Corrosion." A Water Still Used in Connection with This Is Shown in the Background

WHAT IS THIS THING CALLED FATIGUE?

By H. W. Gillett[1]

Most of the failures in springs, axles, shafts, connecting rods and other moving parts made of metals do not come as a result of a smash-up, but are caused by the continued repetition of stresses so low that their effect would be inappreciable if they were not repeated.

In these "fatigue" failures, even a ductile metal finally snaps off short, without distortion, because a crack has been produced, and is propagated till the cross section is cut down. This "short" type of failure, without the distortion of the metal which we see in a broken tensile test-bar, shows the undeformed grain of the metal on the area that held till the final fracture, while the co-acting faces of the previous progressive fracture are usually rubbed smooth, giving a characteristic appearance to such a fracture. Due to the appearance of the final fracture mechanics long ago jumped to the conclusion that the "metal had crystallized under vibration," which it did not do at all. The type of fracture merely revealed the original crystalline structure. The "crystallization" myth has long obscured a realization of the true phenomenon.

The phrase "fatigue," too, is an inaccurate one. Metals do not get "tired," and then rest up. If they are repeatedly overstressed, they begin to develop very tiny sub-microscopic nuclei for failure that in time develop into cracks. "Endurance" or resistance to progressive failure under repeated stress, is a far better term than "fatigue," though "fatigue" is so firmly entrenched in our vocabulary, that it will be a hard term to get rid of.

An airplane propeller, an electric cable swaying in the wind, a railroad rail flexing under the wheel load, or any metallic part subject to many repetitions of stress, has to be designed so that it will withstand those repetitions without failure.

The designer therefore asks the testing engineer to tell him whether or not a given alloy will stand up so as to have the length of life desired. The object of this article is to discuss how far the testing engineer can answer that question to-day.

A definite answer cannot always be given, and the testing engineer will in turn put to the designer some rather embarrassing questions in regard to the actual stresses the part must stand. If the actual stresses are known, however, the testing laboratory can return far more definite answers to the question "How long will it last?" in the case of repeated stress than it can in the case of corrosion, of wear or of service at high temperatures. Ten years ago, the state of knowledge of the endurance of metals under repeated stress was fully as chaotic as it is to-day in regard to these other problems. There is, of course, much more to be learned, but a good many of the fundamental principles are now well understood.

The subject was first studied about 1852 by Wöhler in Germany, and soon after by Fairbairn in England, with apparatus naturally poorly suited to the work. It was only possible to apply measured loads rather slowly, and a test covering a few million cycles was a very extended one in those days.

Wöhler, however, did run a few specimens for a great many cycles, and the data of this first worker in the field indeed gave considerable evidence as to the existence of an endurance limit in steel, though it was many years later before its existence was generally accepted. One of his tests ran over 132 million cycles at 72 r. p. m., i. e., it took $3^1/_2$ years. He spent 12 years in these researches, and died at the age of 94. Workers in the endurance field ought to be long-lived in order to carry their work on to a fair degree of completion!

In modern times, it has been found necessary, on some alloys, to extend the test upward of 500 million cycles before one can feel secure in his results. High speed turbines and airplane propellers turn over very fast, and the useful life of many modern moving parts has to be measured in billions of cycles. One can't tell how an alloy will act in a billion cycles unless he runs it a billion cycles. Hence, each new alloy that falls into a class not previously exhaustively studied, must be run and run and run before the testing engineer can assure the designer that it has the desired properties. Endurance testing is a job for Job, and attempts to speed up such testing have been made, and are still being made, without very much success.

As research on endurance progressed, and many long runs were made, it finally appeared evident that steels, and ferrous alloys in general, have a true "endurance limit." That is, there is some stress below which, no matter how many times the metal is subjected to stress, it is not damaged, and will not fail. It was scarcely 10 years ago that this was proven beyond question, and arguments ceased as to whether any stress, however small, if often enough repeated, would cause failure. With certain limitations as to presence of internal stress, it is nowadays believed that if a steel specimen runs at a given repeated stress for 10 million cycles without breaking, it will never break under that stress.

Belief in this fact is strengthened by a very peculiar phenomenon, less understood than it will be as time goes on, but substantiated beyond doubt. This is the phenomenon of "strengthening by understressing." If a specimen is subjected to a few million cycles of repeated stress just below the endurance limit, it becomes strengthened and hardened (as can be shown by static tests), acting as if it were cold-

How Long Will It Last?
Research and Testing on Alloys for Extreme Conditions

Evaluation of the properties of metals and alloys to resist static stress at normal temperatures has become, through the experience of many years, a well-understood matter. The testing engineer knows how to make the tests, and the designing engineer knows how to utilize the data. But when it comes to methods of evaluation of such properties as resistance to repeated stress, to corrosion, to high temperatures and to wear as well as the question of machinability and of tool life, neither the methods of study and test nor the engineering application of the information are so well understood.

"How long will it last?" is a question which the user of metals often puts to the metallurgical engineer, and one which is seldom easy to answer. Proper engineering design depends very largely on how adequate an answer can be given. Much effort is being put on these problems by individual research laboratories and by committees of technical societies.

[1] Battelle Memorial Institute.

worked, though its dimensions do not change measurably, so that after this treatment it will stand many millions of cycles at repeated stresses so high that if it had not been for the preliminary treatment, it would have failed in a few hundred thousand cycles. With this fortunate fact in view, one can feel confident that a stress can be found at which steel will endure indefinitely, if corrosion or surface damage be prevented.

Most alloys act in this way, and have real endurance limits. There are a couple of important alloys that do not, or if they do, it will be necessary to run tests to many billions instead of many millions to find it out. Duralumin and other aluminum alloys, and monel metal, fall into this category. This does not mean that they cannot be used for service under repeated stress; they can and are. All that is necessary is to so design the part that the life at the required stress will surely be as long as the part is expected to serve. This is what is done with an airplane propeller, forged from a strong, heat-treatable aluminum alloy. The stress-life (stress - number of cycles, or S-N) curve is determined for that alloy, and a prolong from the propeller is made into an endurance specimen, and given a "proof-life" test to see whether that particular propeller has the expected endurance properties. Its safe life can then be predicted. It is etched at intervals to see that no surface cracks are starting and when it has endured so many alternations of stress as to be approaching the failure point, it is retired from service.

Reverting to the case of steel, as representing the more common behavior of alloys in general having a true endurance limit, as has been stated, as long as the stress is below the endurance limit, no damage will ensue. If, on the other hand, the stress is allowed to rise above the endurance limit, damage is done. If, after stressing a specimen somewhat above the endurance limit for, say, a few thousand cycles, the stress is then dropped somewhat below the endurance limit of a virgin specimen, and the test continued, it is found that damage has been done and the piece will fail.

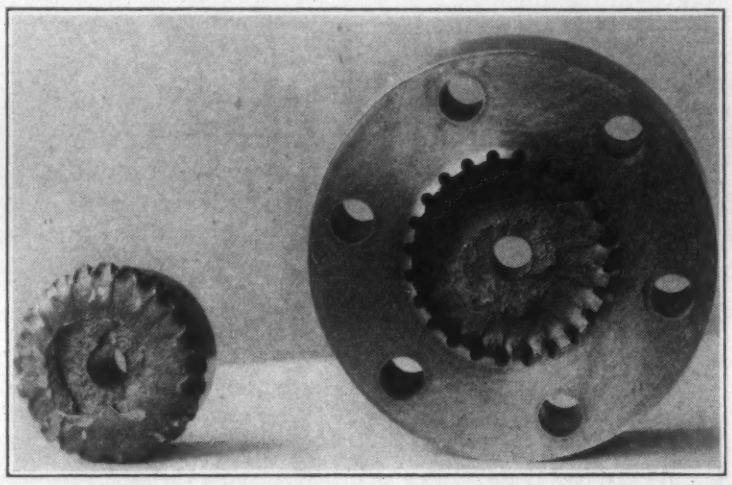


Fig. 1—This Is the Type of Failure That the Engineer Is Trying to Avoid by Use of Endurance Test Data. Multiple Fatigue Fractures Starting from Many Points of High Local Stress. Failure Proceeded Till Only a Small Central Ring Was Left, Which Finally Failed Suddenly. Courtesy of Westinghouse Electric and Manufacturing Company

Hence, the endurance limit is a stress below which everything is lovely, and the metal is getting better instead of worse, but above which damage is being done. This damage may be so slight that it will take many millions of cycles to develop it into a crack and consequent failure, but damaged it is, nevertheless. Hence, it is highly important that the designer and the user shall guard against the possibility of the application of even a few applications of load over the endurance limit.

It can hardly be too strongly emphasized that the endurance limit is a *stress* value. Hence, the designer must know, and not merely guess at, the actual stress to be imposed. Very often the *design* value of the stress is low, but the *actual* stress value, at a sharp shoulder, a key-way, or a screw-thread, for example, is actually way above the calculated value.

The metal will fail if at any point, however minute, repeated stress is applied above the endurance limit.

The testing engineer has to design his testing machines and his specimens so that the actual stress is the calculated stress. He can then determine the endurance limit. It is then up to the designer to fix matters so that the highest local stress is never above the endurance limit. He cannot always do so, for while his design may be perfectly safe for a part with the radius shown on the blueprint at a given fillet, for example, if the machinist makes a square corner instead, or even leaves a rough finish, the local stress may rise above the endurance limit. When it does, failure can ensue.

Right here is one of the weak points of endurance testing. The standard test shows what the metal will stand when everything is in its favor, but it does not show what abuse the metal will stand, how often it can be accidentally taken above the endurance limit without having rapid failure ensue. Alloys differ in their ability to stand such abuse.

The straight endurance limits of steels are (given a properly shaped and polished test bar, with freedom from external notches such as scratches on the surface or internal ones such as inclusions, slag streaks, shatter cracks, etc.) pretty much proportional to the tensile strength or the Brinell hardness. The ratio of endurance limit to tensile strength is around 50 : 100, though it may be as low as 35 : 100 or as high as 65 : 100, so that one cannot dispense with the direct determination of the endurance limit. That is, if only service, without abuse, were to be in the picture, the stronger the steel can be made in tension, the higher its endurance limit.

But this approximation doesn't hold even on the basis of the regular endurance test alone, for quenched, heat-treated steels drawn at so low a temperature or for so short a time that internal stresses are not released.

Even when internal stress can hardly be blamed for the effect, it turns out, in service, that a softer, tougher steel acts better than the one that would be picked from an endurance test alone. This doesn't mean that the information given by the endurance test is wrong, it merely means that it gives one kind of information. So if the service involves only occasional overload or shock, as well as repeated stress at the design load, or if surface notches are to be allowed (thus raising the stress from the design value to an unknown but higher

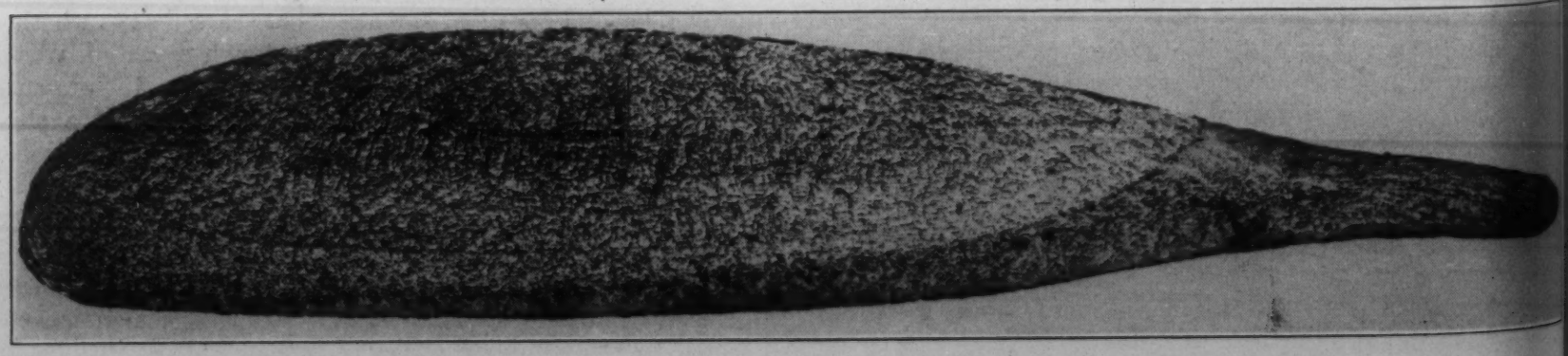


Fig. 2—Another Failure That Is Very Decidedly to Be Avoided. Fracture of an Airplane Propeller. This Failure Crashed an Expensive Plane, and Put the Pilot in the Hospital. Material and Design Were Satisfactory, the Failure Being Due to Local Stresses Set Up at the Stamped Figures and Letters Shown in Fig. 3. Courtesy Bureau of Standards

value) the engineer must temper his enthusiasm for superhard steels which will not stand shock, and are sensitive to the notch effect.

Perhaps some day a notched endurance test will be worked out and standardized that will give the answer directly for such cases, but so far it is necessary to have the data from both an endurance test and a single blow notched bar impact test, and then use a good deal of horse-sense in appraising the type of service so as to pick the optimum.

There are other difficulties with endurance testing. As has been said, the endurance limit is a stress value, and the testing engineer has found that in order to keep from kidding himself and misleading the designer, he must run his test so that he may measure the stress accurately. Hence, he polishes out all transverse scratches that may raise the stress over that calculated, and he uses a small specimen so as to have the loads small enough to handle. It is a ticklish thing to try to apply repeated tension and compression to the whole cross-section of a bar, and secure truly axial loading.

Unless it is axial, he is more likely to be measuring the deviation from axiality than the properties of the material. Moreover, it is not certainly known just how the endurance limit varies if the load is not exactly reversed. That is, 35,000 lbs./in.^{2} in tension to 25,000 in compression may not act just like 30,000 tension and 30,000 compression. Of course it won't if the yield point is 33,000, but even if the yield point were 50,000, it is not certain that the behavior would be the same. So the testing engineer, in order to avoid this variable, chooses, where he can apply it, a rotating beam specimen, since this automatically gives equal tension and compression.

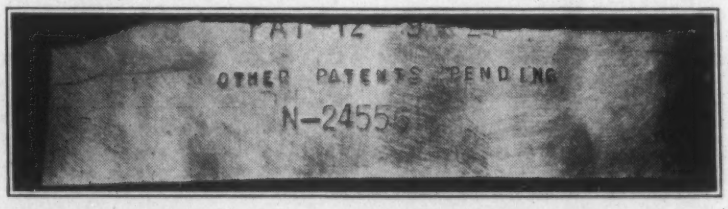


Fig. 3—Stamped Letter and Figures Responsible for the Fracture Shown in Fig. 2. Courtesy Bureau of Standards

In securing the certainty of loading he gets with the rotating beam, the testing engineer meets another major difficulty, especially when he uses a smoothly radiused specimen with only one point of minimum cross-section. The material he is stressing to the maximum, and using in his actual determination of the endurance limit, lies only at the very surface of the rotating beam, and only at the very center of the specimen. Thus he isn't stressing a volume at all, but only one mathematical circle about the middle of his test piece. He can improve matters a bit by using a tapered cantilever type of specimen, but even then the material actually at maximum stress would ordinarily go in the eye of a needle. Husky test pieces, with heavy loads can be, and are, used for special purposes, but at best the rotating beam does not test a large volume of material, nothing at all of the order of the volume tested in a static tensile test.

An interesting advance along this line has been made by the Bureau of Standards, which has rigged up the usual rotating beam testing machine to use so long a length of wire that the weight of the specimen itself counts in the loading, and so increases the load toward the center of the span that an unradiused test specimen can be used without breaking in the grips. While this scheme would be difficult to apply to bars of large cross section, and it still tests only the surface, it does test long lengths, and is certainly a step in the right direction, where applicable.

Hence, the regular endurance test has to include a lot of test bars if one wishes to study the question of the presence or absence of internal flaws that might and doubtless do, affect the endurance in service. The uniformity of the results of an endurance test, the way they form a nice, smooth curve in homogeneous material, or a wide scatter-band in non-homogeneous material, would be one of the most searching quality tests that could be imposed if it weren't so awfully expensive and time-consuming to make them.

Endurance testing is, therefore, so far, more of a proposition for the research laboratory, to establish the broad principles of what a given type of alloy or a given heat-treatment will do in respect to endurance, than it is a method of inspection testing to tell the quality of a given lot of metal.

An endurance test is made by running a bar at a high stress till it breaks and noting its life, running another at a lower stress, and noting its life, and so on, at progressively lower stresses, till the bars cease to break and run for as many millions or billions of cycles as it has been decided to extend the test. The stress-life (S-N) curve is then plotted, and if the curve is truly horizontal and parallel to the N axis, then the endurance limit has been found.

The old "vibratory test" in which a specimen was subjected to repeated stresses so high that it broke in, say, a few thousand alternations of stress has been, or at least should be, abandoned, because the S-N curves, above the endurance limit, may cross, and such tests may not even rate competing materials in the proper order. The search nowadays is for the safe stress—the endurance limit—and finding it involves running some specimens for a long, long time *without* fracture. Many attempts have been made to find something, like the development of heat in the specimen due to slip, a change in electrical resistance, or some other property that would, in a relatively few cycles, tell whether anything was occurring that would ultimately cause failure.

Fig. 4—Fatigue and Corrosion-Fatigue Testing Equipment, Formerly Used in Gulf Oil Company Work at Mellon Institute, Pittsburgh, Now in the New Research Laboratory of the Gulf Oil Company, Pittsburgh

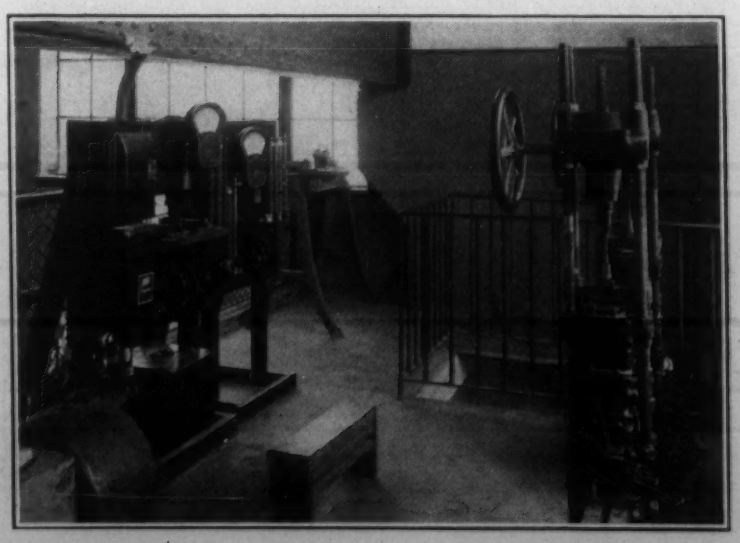


Fig. 5—Two Haigh Machines at the Bureau of Standards, Washington. One Machine Is Directly Back of the Other at the Right; Control Equipment at the Left

But the development of the nuclei for failure into perceptible cracks comes so slowly that such methods are yet unavailing. Several of them, when tested on materials whose break-down in an endurance test happens to coincide with the beginning of slip, look good for a while, but as the study is extended, alloys are found on which quite erroneous indications are shown. The longest way round is still the shortest way home in endurance testing.

The obvious way to let the nuclei develop, and still get the test done in a hurry is to use a great number of cycles but apply them awfully fast. Hence, various schemes are being used to speed things up. Magnetic type testing machines are being run at 30,000 cycles per minute and air-driven specimens are being made to vibrate of themselves at great speed, something like a tuning fork. (See illustration page 145, October 1929 issue, METALS & ALLOYS.) Unfortunately, the problems of stress measurement in the magnetic machines, or of making large enough specimens of steel vibrate in large enough amplitude so that good stress-measurement can be made in the air-driven type, are extremely difficult. Some of the results to date, taken at face value, are discouraging in that they seem to give endurance limits at these high speeds that are far above the true endurance limits at the lower speeds mostly used in actual service. Hence, the methods would give results unsafe for design use unless a correction factor can be found, and the establishment of a correction factor entails recourse to the old, tedious, slow speed methods.

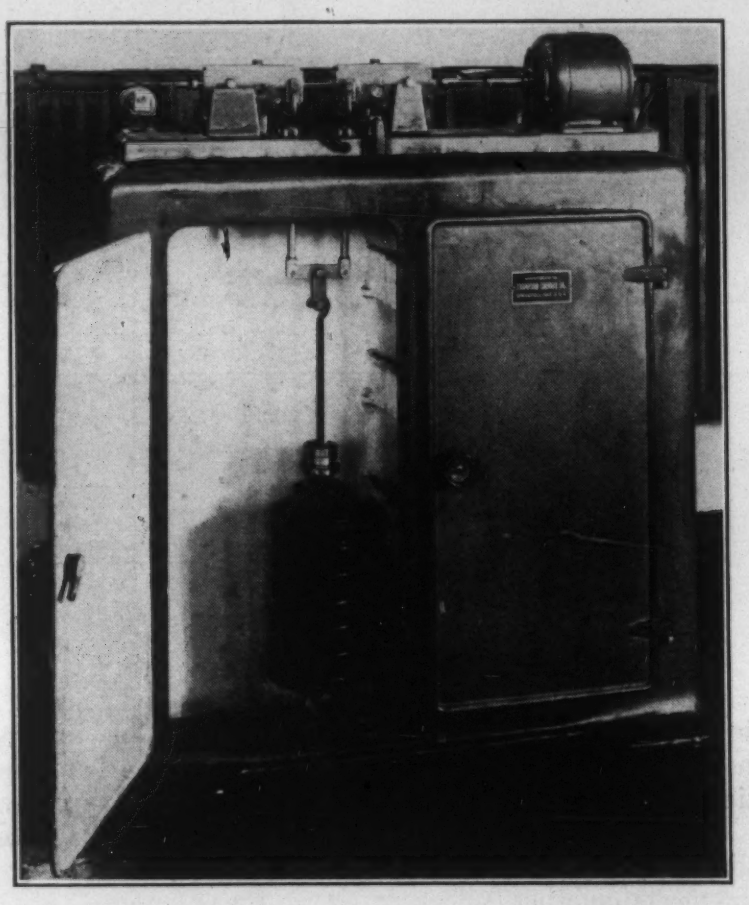


Fig. 6—A Modern Endurance Testing Machine, in Use at the Laboratory of the American Steel Foundries

It does seem possible to speed up the testing somewhat, as McAdam has reported normal results with tests run at 10,000 r. p. m. instead of the usual 2000 r. p. m. or less. But great care has to be taken in speeding up any given testing outfit, to see that no harmonic vibrations are set up that impose actual, and unknown, stresses on the specimen above those calculated. Incidentally, harmonic vibrations must be just as carefully guarded against in practice. Three of the four crankshafts of the Graf Zeppelin broke during one of the early trips because, when in actual use in the dirigible, harmonics were set up that were not present in block testing, with a rigid foundation, and whose presence was not suspected till too late.

Another difficulty in endurance testing crops up when the dimensions of the material do not allow the use of the rotating beam specimen, as is the case with thin springs. Here it is necessary to use a repeated bending test, and in such methods it is generally more convenient to measure a given deflection rather than a given load. In that case, to transfer the figures to stresses, one has to know the modulus of elasticity to a refined degree, and that is in itself, not an easy task.

The difficulties are great enough when one has only to deal with stresses. But the situation is complicated by the fact that if corrosion is allowed to act, simultaneous with repeated stress, the endurance limits of alloys subject to corrosion, are not what they are when corrosion is absent, but distressingly much lower, as McAdam has so brilliantly shown. One steel that in the absence of corrosion had an endurance limit of 108,000 lbs./in.^{2}, had but a 12,000 lbs./in.^{2} endurance limit under conditions where the steel could rust. Hence, one has to pick out, to carry out a "corrosion-fatigue" test, just the corrosive conditions to be met, which brings one face to face with the usual difficulties of corrosion testing, and involves many obscure problems as to the effect of rate of repetition of stress and so on.

Between the standard laboratory test on a notch-free, perfectly polished specimen of spring steel, and the results in service, there is quite a gap. Rough surfaces, the presence of bolt holes, surfaces decarburized in heat treatment and not removed, or the presence of corrosion, will all drop the calculated stress that the spring will withstand, far below the laboratory value. This fact points out obvious means of improving spring design and fabrication so that the steel may have a chance to act as it does when it is on its good behavior. The amount of surface notching the steels will stand when they are abused, needs much further study. There is good evidence that internal quenching stresses adversely affect the endurance of heat-treated steels, and it takes longer tempering to remove such stresses than is usually

Fig. 7—Flexural Fatigue Machine at Bureau of Standards for Thin Specimens. The Deflection Is Regulated by the Position of the Crank-Arm on the Head Attached to the Motor Spindle, and Is Measured by an Optical Lever System. The Mirror for This Moves with the Specimen

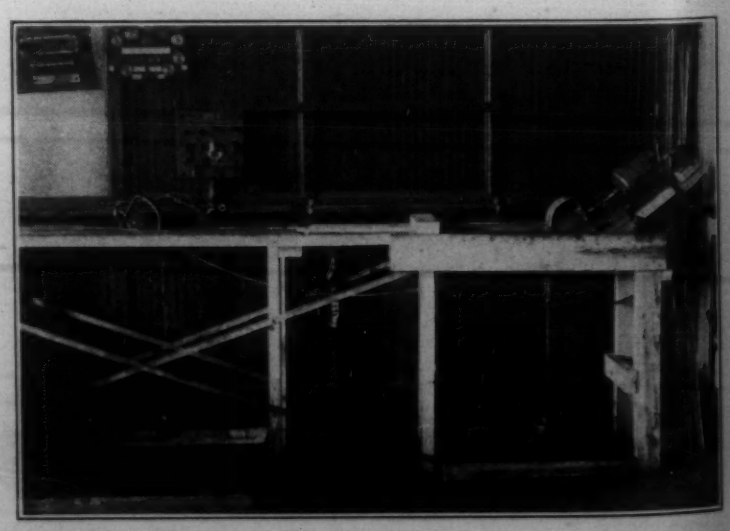


Fig. 8—Rotary Beam Endurance Machine Rigged for Tests on Long Wires. The Specimen is 66 Inches Long. Bureau of Standards

given. Different alloy steels probably vary greatly in their susceptibility to surface notches or to internal ones, i. e., inclusions, as well as in their ability to attain relief from internal stress without softening too far. These matters deserve more attention than they are getting.

In spite of all the drawbacks, the need for the results of endurance testing is so plain and the value of the results so great, that vast amounts of research have been put on the problem in America, England and Germany. This is a field in which the English-speaking nations have led, in recent years, though Wöhler first showed the way. Germany is now intensively studying the problem. In America, Prof. H. F. Moore and co-workers at the University of Illinois, and J. B. Johnson at the Army Aircraft laboratory at Dayton, various workers at the Bureau of Standards, at the Research Laboratories of the Westinghouse Company, the Bell Telephone Company, the Aluminum Company of America, (see illustration page 719, September issue, METALS & ALLOYS) the General Electric Company, the National Tube Company, the University of Wisconsin, Lehigh University and others, have covered the field very thoroughly. The results have been well substantiated by data from an almost equally long and brilliant list of English investigators.

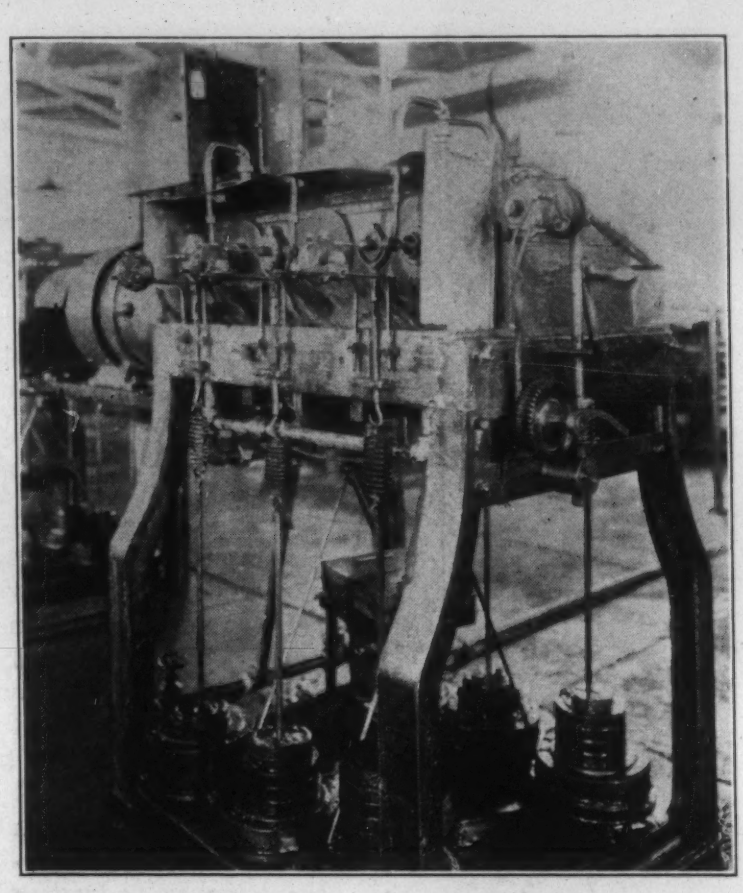


Fig .9—Corrosion-Fatigue Testing at the Naval Experiment Station, Annapolis

The designer can get the gist of the endurance situation from a concisely-written "Manual of Endurance of Metals Under Repeated Stress," by H. F. Moore (Engineering Foundation, New York, 1927). The Fatigue Research Committee of the American Society for Testing Materials made a report in June, 1930 in which the accepted facts as to endurance of metals are briefly and clearly stated.

For a more extended discussion of the subject, from the testing engineer's and the metallurgist's angle, two books with the same title, "The Fatigue of Metals," one by H. F. Moore and J. B. Kommers (McGraw-Hill Book Company, New York, 1927), the other by H. J. Gough (Van Nostrand, New York, 1924) are available.

Both of these contain tables that summarize the known quantitative facts on many engineering alloys. The individual original researches from which the present situation can be pieced together, are published, in this country, largely in the Bulletins of the Engineering Experiment Station of the University of Illinois, and in the Proceedings of the American Society for Testing Materials. The A.S.T.M. published in 1929 and 1930 (and plans to do so in 1931) a collection of abstracts on the literature of endurance. Such abstracts appear, month by month, as the articles are published, in the abstract section of METALS & ALLOYS, and books and monographs on the subject are promptly noted in the Book Reviews.

While, like Oliver Twist, the designing engineer is always asking for more, and more refined, endurance data, still he has, within the past 15 years, been given information of incalculable practical importance, and testing methods have been worked out so that the way is clear to get much of the further data needed.

Nor has the designing engineer been slow to utilize the information. He is designing more and more, not on vague factors of safety, but on actual endurance limits. And perhaps the most important feature is that the information brought out by endurance research has driven, or, at least is driving home, the necessity for actual knowledge of local stresses, avoidance of internal or external stress raisers, dirty steel and sloppy machine work. Aircraft connecting rods are scrupulously polished, and the metallurgist is relieved of much blame, formerly placed on him for faulty material, that is now shown to be ascribable to poor surface finish, sharp corners, key ways, etc.

Extensive as the investigations on endurance have been, and copious as have been the publications—the writer must have 30 lbs. of books and reprints on endurance—there is still much to be learned. Information is needed on the relationship between completely and incompletely reversed stressing, between rotary beam, axial and torsional loading; as well as on combinations of different types of loading; on the susceptibility of different alloys to the propagation of a notch; on actual local stresses in such things as rock

Fig. 10—A Battery of Endurance Testing Machines in Use at Wright Field, Dayton, Ohio

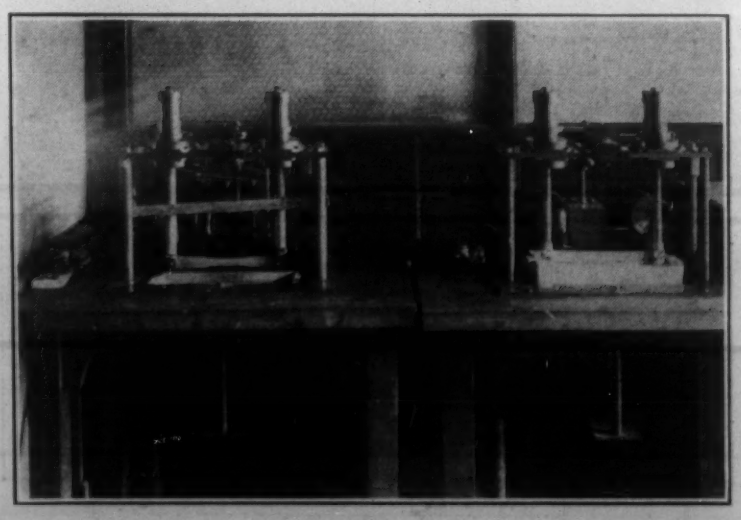


Fig. 11—Apparatus at the Bureau of Standards for Study of Fatigue under Intermittent Corrosion. The Tensile Specimen Is Bent Back and Forth, and a Corroding Solution, in the Rectangular Tank, Is Raised and Lowered so as to Wet the Specimen at Intervals

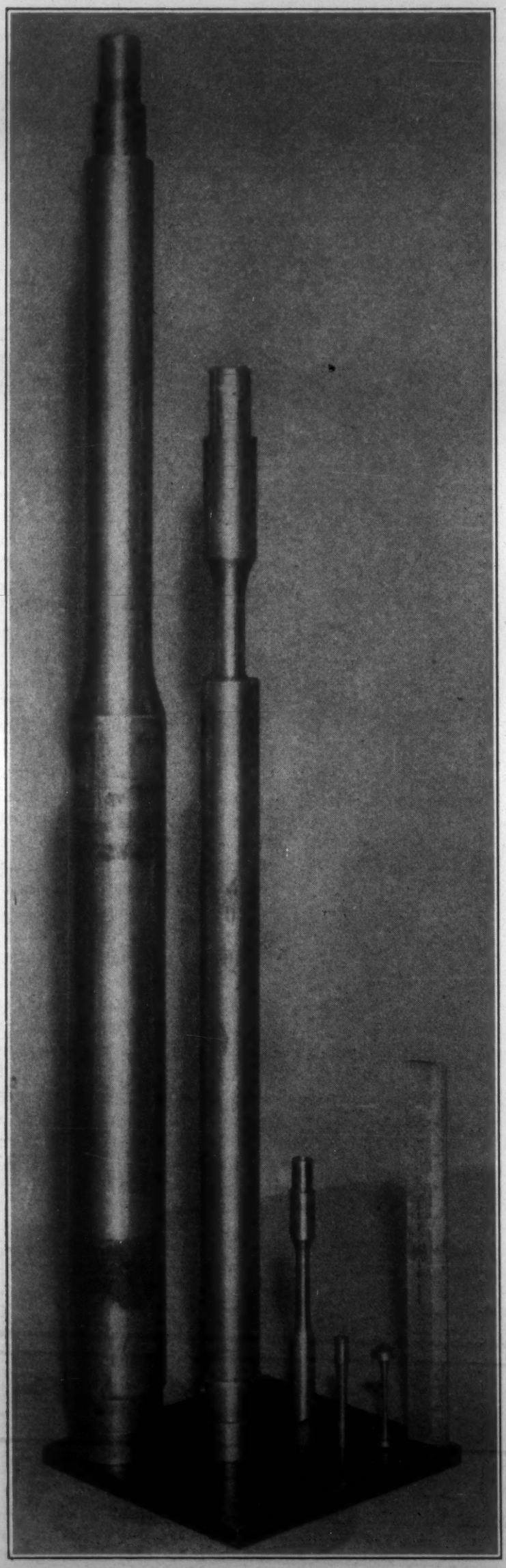


Fig. 12—Comparison of Sizes of Fatigue Specimens Used at Westinghouse Electric & Manufacturing Company. The Two at the Right Are the Size Normally Used in Fatigue Testing

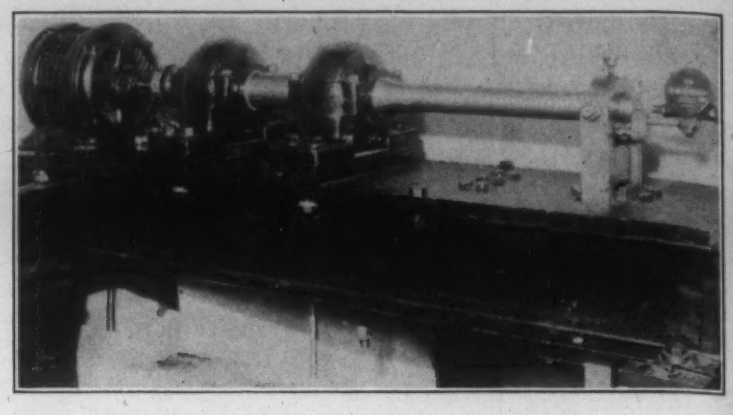


Fig. 13—Endurance Testing on Large Specimens—2 1/4" Diam. Westinghouse Electric & Manufacturing Company, East Pittsburgh

drills and railroad rails. More data are needed on the effect of combined repeated stress and corrosion, and on the effect of over- and under-stressing.

We need more rapid methods of testing, cheaper endurance machines (at around $400 per unit for the most-used rotary beam machines and several thousand for an axial-loading type, it can be seen that the batteries of machines shown in the illustrations represent a considerable investment), specimens that are cheaper to prepare, and it would help a lot if some entirely reliable, accelerated testing method could be devised that would give true results in all cases.

If some method could be found for examining a wire rope, a connecting rod, a spring, a rail or other repeatedly stressed part that has been in service, to find whether or not it has been so overstressed in some minute portion that a submicroscopic nucleus for fatigue breakdown has started to develop, even though no actual crack has yet occurred, it would be a great step toward safety. Much work has been done on magnetic, electrical and other methods. Some of these apply after a real crack has started, but none fill the bill completely. All that can be done is to design properly, and then see that the stresses are not allowed to go above the design value from any cause.

When the stresses cannot be so controlled one must use a larger factor of safety and choose a material that will not be too severely damaged by the overstress. Too little is yet known about the relative damage by overstress in various alloys. Ordinarily, toughness is an asset, but still some alloys that would ordinarily be called tough, are notch-brittle.

Were it possible more cheaply and quickly to extend endurance tests to many billions of cycles where they are now run to a few millions, we could learn more about the endurance properties of non-ferrous metals. Steels act pretty much alike, in the absence of corrosion, and one can make a tolerable guess, from known tensile properties, as to how they will behave under repeated stress. Even in the case of corrosion, it is known that truly corrosion-resistant steels

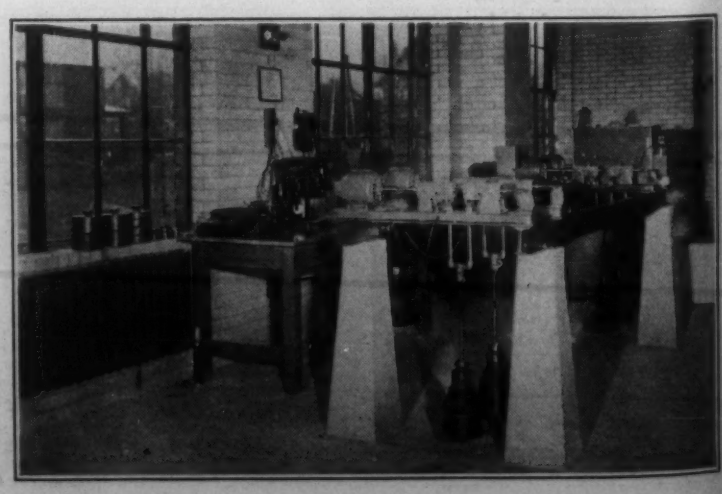


Fig. 14—Endurance Testing at Low Temperatures. The Machine Enclosed by the Box Is Operating at —40° C. Battelle Memorial Institute, Columbus, Ohio

such as the austenitic nickel-chromium group, have "corrosion-fatigue" limits nearly up to the endurance limits in air. It is also known that suitable inhibitors, can, under certain definite limitations, be successfully used to create a corrosion-resistant coating on ordinary steels. Then we know that proper coatings, like a plated zinc coating which does not form a brittle iron-zinc alloy layer, give good protection as long as they last, against corrosion, and hence against corrosion-fatigue of steel.

But the non-ferrous alloys do not follow as well-defined general laws as do the steels. Each alloy is a law unto itself. In general, the endurance limit, where one exists, is a smaller proportion of the tensile strength than is the case with steel, and the improvement in endurance limit by cold-working may be marked, or almost non-existent. The behavior of many of the non-ferrous alloys on over- and under-stressing is not yet clearly established.

Endurance data on any alloy at high and at low temperatures are very scarce, and are being asked for by the engineer. Testing difficulties are many, but even these problems are being attacked and progress is being made, particularly at the University of Illinois and at Battelle Memorial Institute.

There are hundreds of endurance machines in the metallurgical research laboratories of this and other countries, and problems enough to keep them all busy for years to come. Engineering knowledge of the behavior of metals under repeated stress is still sketchy, but no longer entirely chaotic.

While it is impossible to list here anything like the range of alloys on which endurance data are available, a few representative figures may be given. Data on wrought steel are best considered from the point of view of a comparison with the static tensile strength.

Ingot iron has an endurance limit, in completely reversed bending of around 60% of its tensile strength (even though this is above the proportional limit). As the carbon increases, in annealed or normalized steel, those of 0.10–0.15% C usually run about 50% of the tensile strength, but as the carbon increases further the endurance ratio tends to drop to around 40%, and figures as low as 28% are recorded.

Raising the carbon does raise the endurance limit, in absolute value, but it is not the most effective way of improving the endurance properties. Cold working, again, raises the endurance limit, in absolute value. Cold-drawn ingot iron has an endurance ratio of 45%, and this ratio holds fairly well for cold rolled or cold-drawn steel, though the possibility of internal damage by excessive cold work and the introduction of internal stresses make it necessary to keep the eyes open when using this method of getting better endurance figures.

When high endurance is required, quenching and tempering of carbon or alloy steels is generally resorted to. If the steels are clean, as free as possible from non-metallic inclusions, shatter cracks or internal strains, the endurance limit stays at 45–55% of the tensile strength, up to a tensile strength of about 200,000 lbs./in.^{2} Above that strength,

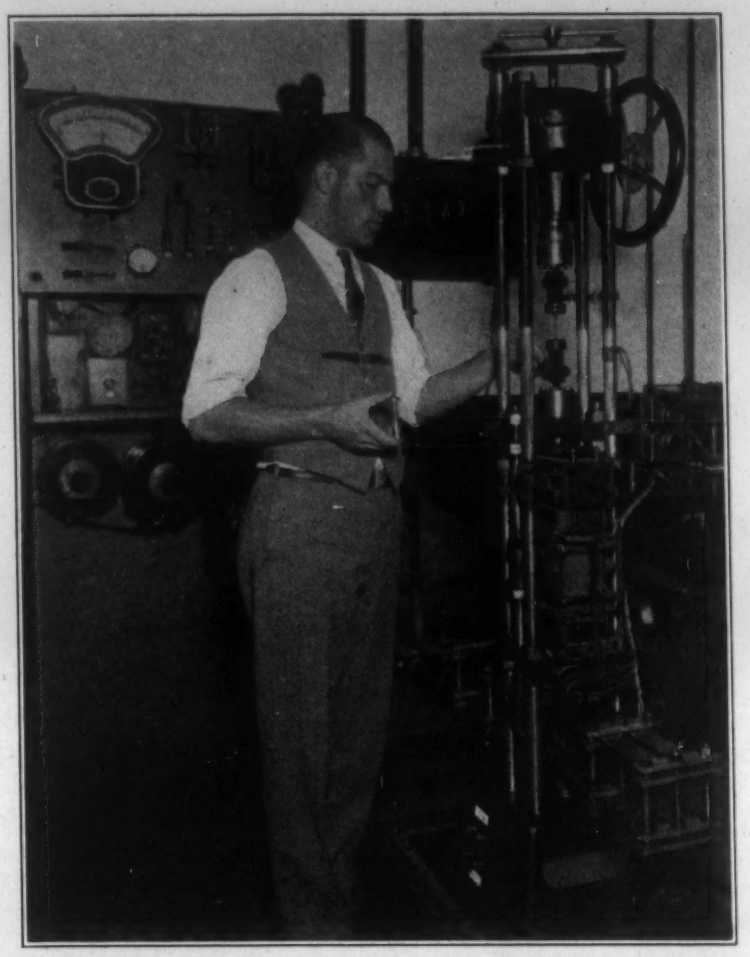


Fig. 16—A Haigh Axial Loading Endurance Machine at the Westinghouse Electric and Manufacturing Company, East Pittsburgh

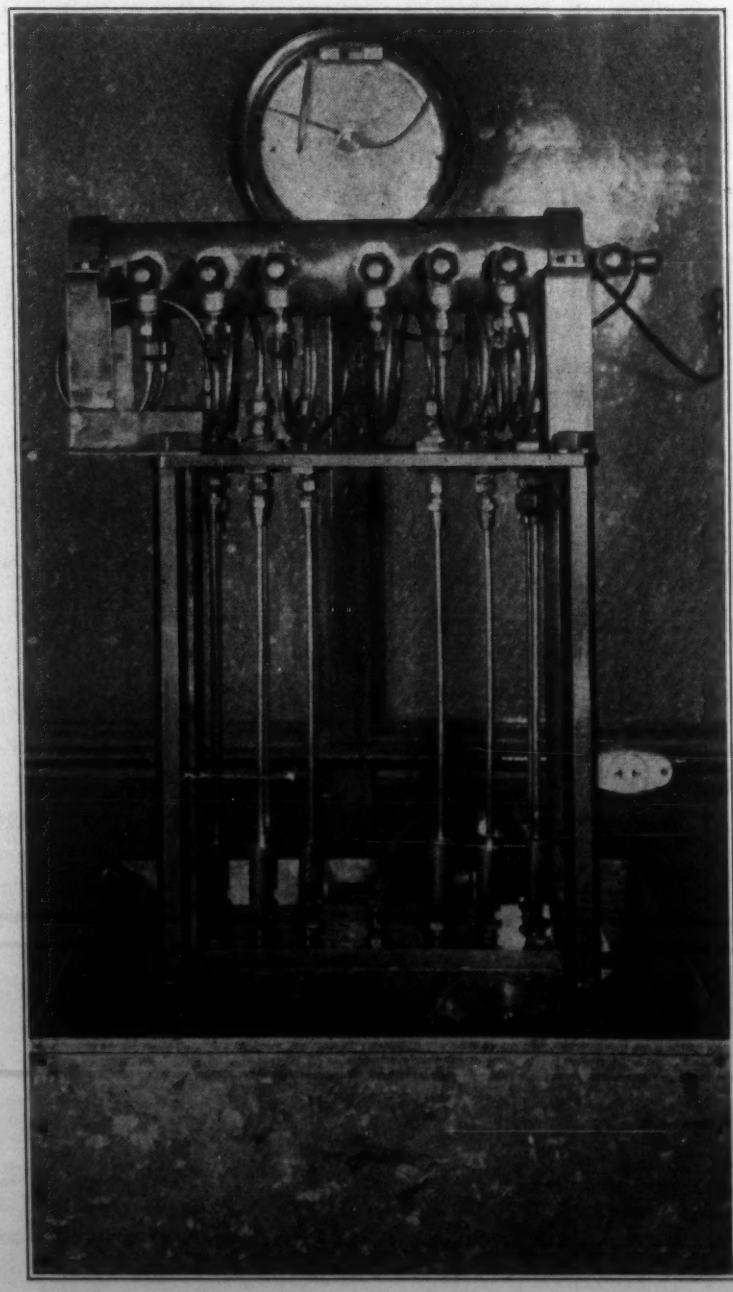


Fig. 17—Vibratory Testing of Refrigerator Tubing. Frigidaire Corporation, Dayton, Ohio

Fig. 15—Cantilever Rotating Beam and Deflection-Type Fatigue Machines in the Bell Telephone Laboratories, New York

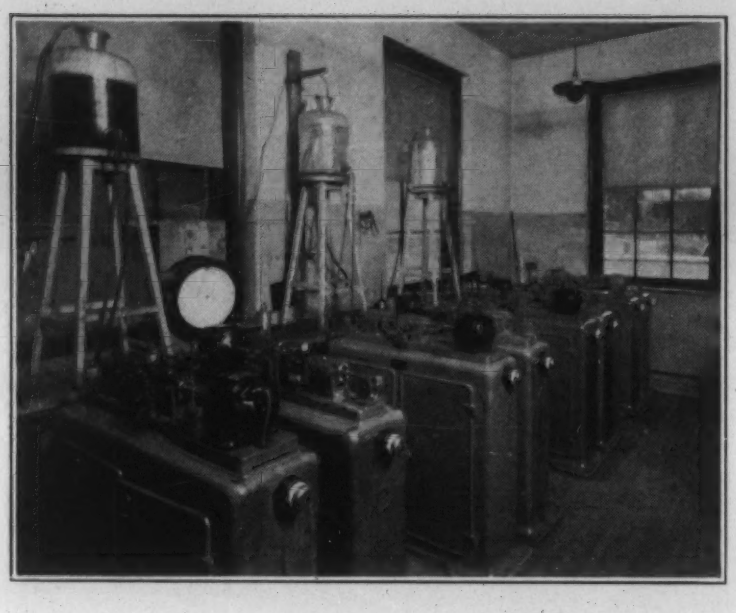


Fig. 18—Corrosion Fatigue Set-Up at Laboratory of the National Tube Company, Pittsburgh

as with steels of, say, 275,000 lbs./in.² tensile, the endurance ratio is likely to be lower, and the endurance limit seldom rises much above 110,000 or 115,000 lbs./in.², probably through the effect of internal stress. Prolonged tempering at low temperatures so as to maintain a high tensile strength has sometimes allowed the production of specimens with around 125,000 lbs./in.² endurance limit.

While there seems to be a tendency for the endurance ratio to be higher in a sorbitic steel than in a pearlitic one, the presence of troostite, martensite or austenite does not notably affect the endurance ratio. The austenitic stainless steels show about the usual 50% endurance ratio and the endurance limit in completely reversed bending may be well above the proportional limit, as is the case with pure ferrite.

Carburizing or nitriding offers distinct possibilities for service where the maximum stress is at the surface. Carburized steels can be made to give 55,000 lbs./in.² endurance limit, and a nitrided steel has given as high as 84,000. There is always a danger of starting a notch in a brittle coating which will reduce the endurance limit, and the brittle iron-zinc alloy layer on a hot-galvanized or sherardized steel is responsible for reducing the endurance limit from 60,000 to less than 45,000 lbs./in.²

Properly annealed cast steel usually gives endurance limits of about 40% of its tensile strength, an 80,000 lbs./in.² tensile steel showing 32,000 lbs./in.² endurance.

Cast iron has not been any too thoroughly studied. Endurance limits found for different grades range from 7000 to 24,000 lbs./in.², and from 33–57% of the tensile strength. Thus the better grades of high strength cast iron have endurance properties within reaching distance of cast steel, and some cast irons, at least, are but little affected by notches and square shoulders.

There seems to be an almost complete absence of data on the endurance properties of malleable iron. Schwartz gives as the results of a test on a single lot of malleable, but one said to be typical, an endurance limit of 25,000 lbs./in.² As he elsewhere states that typical malleable runs about 51,000 lbs./in.² tensile, 12% elongation, this endurance ratio is nearly 50% of its tensile strength.

In dealing with any of these ferrous materials, it is always necessary to recall that when corrosive conditions of service are involved, they all tend to come down to a much lower corrosion-fatigue limit, no steel that is not truly corrosion-resistant having a corrosion-fatigue limit much over 25,000 lbs./in.² and often lower. Heat-treatment is not of much value in this connection. Even stainless steel has its endurance limit rather badly reduced, while the austenitic stainless type, truly corrosion resistant under most service conditions, loses but little in endurance limit even though corrosive conditions obtain.

The situation in regard to non-ferrous alloys is very complex. The endurance limits are generally rather low, and the effect of cold working is not always of particular benefit. Alpha brass, for example, has its endurance scarcely raised at all by cold working. Some non-ferrous alloys of 90,000 lbs./in.² tensile strength have endurance limits under 15,000 lbs/in.² Soft copper has an endurance limit of around 10,000 lbs./in.², but this can be somewhat improved by cold working and proper stress-release.

Nickel and especially monel metal, though probably not having a real endurance limit, yet will stand, on a basis of a 500 million cycle test, 25,000–35,000 lbs./in.²

There is little data on cast bronzes, but properly annealed cast aluminum bronze will give 25,000 lbs./in.² endurance limit.

Most of these non-ferrous alloys are corrosion resistant, and have fairly respectable corrosion-fatigue values.

Heat-treated duralumin shows some peculiarities in endurance, different lots acting differently for no apparent reason. In general, the endurance limit, though none too well marked, is generally taken as around 15,000 lbs./in.² on a 500 million cycle basis. Propeller forgings usually give around 10,000 lbs./in.² on that basis. Some wrought magnesium alloys show similar values. All the light alloys would have decidedly lower corrosion-fatigue values, though "Alclad" duralumin (coated with pure aluminum) can probably withstand 10,000 lbs./in.² under quite severe corrosive conditions.

Cable sheath alloys of lead alloyed with a little antimony may have endurance limits of only 450 lbs./in.² or even less, but lead calcium alloys with only 0.04% calcium, can be given endurance limits of 800 lbs./in.²

Engineers are more and more coming to the realization that the endurance properties of metals are determinable, and that fatigue failures need no longer be classed entirely as an "act of God," but are almost as avoidable, with proper utilization of known facts, as the static failure of a bridge member is.

Metallurgists and engineers are more and more coming to agree with Aitchison,[2] who recognized the situation ten years ago, and said, "The fatigue range is a property of steel which is of most vital importance, it is really the most important property of steel to the designer, particularly of engines.

"For statically loaded parts the proof stress is the most important property . . . For parts loaded dynamically, the fatigue range is of paramount importance. . . In order,

[2] L. Aitchison, Engineering Steels. McDonald & Evans, London, 1921, pages 135–138.

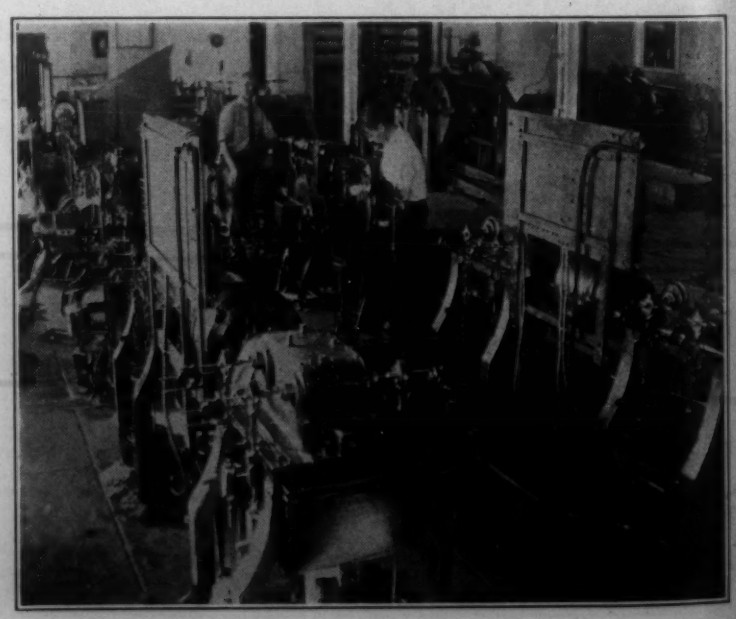


Fig. 19—A Variety of Fatigue and Corrosion-Fatigue Machines at the Naval Experiment Station, Annapolis

however, to ensure that the steel shall be in its best possible condition, the notched bar test is most valuable.

"These three properties—the proof load, the fatigue range and the notched bar value—appear, therefore, to be the real criteria which the engineer should apply to his steel."

Not all engineers will agree with Aitchison in regard to the substitution of the proof stress for the ordinary tensile test, and the notch-bar impact test is, unhappily, so poorly standardized that comparable data are all too scarce. Endurance testing, however, is in a more fortunate condition. By using a little horse sense in the application of well-known fundamental principles, two observers working on the same lot of metal, even though with different sorts of testing machines and different test pieces, will report closely agreeing endurance limits. In other types of severe service such as under corrosion, under abrasion, or under high temperature, where we are anxious to know how long a part will last, or at least if it will last for the useful life of the apparatus, laboratory tests seldom return satisfactorily agreeing results and extrapolation to service is attended with far greater uncertainties.

Hence, by comparison, at least, the research work on resistance of metals to repeated stress, incomplete as it is, has yet accomplished much of value to the engineer and to the user of metals. And it will accomplish more.

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Survey of Cupola, Tap-Out and Slag-Hole Blocks to Ascertain Basis for Establishing Simplified Practice Recommendation now under Way

The joint committee on foundry refractories, sponsored by the American Ceramic Society and the American Foundrymen's Association, recently requested the coöperative services of the division of simplified practice of the Bureau of Standards, Department of Commerce, with the view to establishing a simplified practice recommendation covering the sizes and shapes of cupola blocks, tap-out blocks and slag-hole blocks.

In compliance with this request, a questionnaire has been prepared and is now being circulated among the manufacturers of this product requesting that they submit to the division, for compilation, a list of refractory shapes manufactured for cast iron foundries, together with their dimensions and the number manufactured per year. The manufacturers have also been requested to furnish a list of sizes of tap-out and slag-hole blocks, along with sketches showing the general design of each.

◆ ◆ ◆

Frank A. Shute has been appointed the metallurgist of the roll and machine works of the American Sheet & Tinplate Company at Canton, Ohio. He was transferred from the main research laboratory of the company in Pittsburgh.

Frank A. Shute

R. S. Archer, who was formerly with the Aluminum Company of America, has recently been appointed Director of Metallurgy for the A. O. Smith Corporation.

Dr. S. L. Hoyt, a member of our Editorial Advisory Board, is a new member of the metallurgical staff of the A. O. Smith Corporation. Until lately Dr. Hoyt was connected with the Research Laboratory of the General Electric Company.

Walter E. Jominy is now on the metallurgical staff of the A. O. Smith Corporation. Previously, Mr. Jominy was at the University of Michigan in the Department of Engineering Research.

One of the important developments in recent years has been the demand from the industries for men with graduate training. This is reflected in the growth of the graduate work of the Department of Chemical and Metallurgical Engineering of the University of Michigan. During the present academic year there are 51 graduate students enrolled, of whom 19 already have the Master's degree and are working for the Doctorate.

The East Engineering Building, which is shown in the illustration, gives unusual facilities for advanced laboratory work.

The Department of Engineering Research has important contacts with the chemical and metallurgical industry and several fellowships and research assistantships will be available for graduate students next year. Application should be made by March 1st. Information may be secured by writing the Chemical Engineering Department, University of Michigan, Ann Arbor, Michigan.

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Forecast of the Ornamental Iron, Bronze and Wire Industry

By William A. Boesche*

During the past few years the metal worker has shared more and more in the equipment of new buildings with stairways, grilles, balconies, chandeliers, store fronts, marquises, spandrels, etc.

The past year has proved beyond doubt that metals are being called into increasing use in both home and building construction and decoration. If private enterprise in 1931 follows the example of the government in speeding up building activity then we have every reason to believe that we are approaching a building boom that will be reflected in a quickening of almost every line of endeavor. I look for this building boom to bring us some swift changes in architectural style. New fashions that would otherwise receive gradual expression in the normal course of building activity will be called into immediate use and the trends of to-day will become the realities of to-morrow. The present marked trend toward the increasing use of metals for structural and decorative purposes will be strikingly emphasized when the materials now on hand are called into use. The metal facings on the modern skyscrapers even now suggest the all-metal building. Indeed, the all-metal building is already far more a fact than a vision. The famous "Iron Church" in Cologne, Germany, built entirely of metal inside and out, is attracting the attention of architects the world over. A new apartment building in Chicago, constructed entirely of iron, bronze and steel, is nearing completion. Who can say that these structures do not mark the dawn of a 20th century "Iron and Bronze Age" more typical even than the prehistoric periods we know by that name.

* President, National Association Ornamental Iron, Bronze and Wire Manufacturers.

A.S.T.M. Symposium on Welding

There will be a Regional Meeting of the American Society for Testing Materials at the William Penn Hotel, Pittsburgh, Wednesday, March 18. Beside the usual spring group meeting of many committees, there will be a Symposium on Welding, in which the American Welding Society is coöperating.

At the morning session, F. T. Llewellyn, Technical Adviser to the President, U. S. Steel Corporation, will give a paper comprising an Historical Introduction and General Survey of Welding.

Dr. F. N. Speller and C. R. Textor, National Tube Company, will discuss Quality of Materials for Welding, and A. M. Candy, Westinghouse Electric and Manufacturing Company, will describe Technical Examples of Modern Welding Practice.

The afternoon session will deal with Inspection and Testing, including Fatigue and Impact Tests, X-Ray Testing, Magnetic Testing, Stethoscopic Examination and Practical Inspection.

There will be an informal dinner in the evening.

ECONOMICS OF TUNGSTEN*

By Paul M. Tylert

Tungsten is distinctly a modern metal. The Swedish chemist, Scheele, discovered it as far back as 1781 and Mushet, a British steel maker obtained a patent on a self-hardening tungsten steel in 1857, but the commercial development of the tungsten industry has all taken place in the twentieth century. For many years tungsten minerals were known merely as troublesome impurities in the tin mines of Cornwall and Saxony. Gradually a small demand developed in connection with fixing the colors of cotton goods and later for fire-proofing clothing and draperies for theatrical purposes. Meanwhile research was in progress on tungsten alloy steels. It was used in Germany in rails and in the 90's some quantity was said to be used in armor plate, armor-piercing projectiles, and heavy guns. The real birth date of the industry, however, was 1898. In that year, F. W. Taylor, the father of scientific shop management and motion study, in collaboration with Maunsel White discovered a steel which would permit metal-cutting operations at high speed. Thenceforth tungsten has been one of the dominant factors in the new era of mass production.

In ordinary metal forming operations the productivity of men and machines has been multiplied at least five times simply by using tungsten alloy steels instead of plain carbon steel. Had tungsten not been available there is some doubt whether the automobile and countless other mechanical aids to our present-day industrial and social life would have become available quite yet to the average American family. Tungsten in amounts up to about 1½% is used in hack saw blades and power saws. The original Mushet steel contained 6% of tungsten and the Taylor-White tools contained 8½% but around 18% is generally used in modern high-speed steel tools which must hold their cutting edge at temperatures that render plain carbon steels almost as soft as lead. Most of the successful substitutes for high-speed steel such as stellite also contain tungsten and recently, within the last two years, a new tungsten-containing cutting agent has come into service. Tungsten carbide is the hardest of man-made materials. It exceeds the sapphire and approaches the diamond in hardness. Bonded with cobalt it can be used to cut a thread on glass or porcelain and it retains its keen edge when employed for cutting hard rubber and ivory. Fragments of tungsten carbide are even used instead of diamonds in drill bits for boring oil wells and prospect holes.

Tungsten filaments for incandescent electric lamps were successfully introduced in 1907 and here again the use of tungsten resulted in a marked economy of human effort and mechanical energy. The current efficiency of tungsten lamps is two to three times that of the carbon lamps that they displaced; moreover they last much longer and give a better quality of light.

By far the greatest use of tungsten is in the steel industry chiefly in high-speed steel and to a less extent in other tool steels and in magnet steels (the latter containing 0.8 to 8.0% W). The use in "Stellite," a cobalt-chrome alloy containing usually at least 5% tungsten, has been mentioned and tungsten appears as an alloy in non-warping valves for internal combustion engines (especially for airplanes), in electrodes for electric welding, in electrical contact points (replacing platinum), for targets and electrodes of X-ray (Roentgen) tubes and vapor-type electric lamps. Incandes-

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† Chief Engineer, Rare Metals & Non-Metals Division, Bureau of Mines.

Table I.—World Production (as shown by sales or exports) of Tungsten Ore, 1905–1929, in Metric Tons of

	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920
Asia:																
Japan	43	43	64	200	265	249	260	204	257	204	389	730	763	629	574	170
Chosen (Korea)	...	...	...	...	...	...	...	...	...	...	67	555	919	1,100	197	5
China	...	...	...	...	...	...	...	...	...	18	35	109	1,361	10,577	2,654	4,712
Tonkin (Indo-China)	...	...	...	...	...	17	...	73	127	162	333	343	433	378	284	284
Burma and Shan States	...	137	...	...	...	369	1,015	1,901	1,572	2,166	2,464	3,464	4,226	4,138	3,623	2,983
Siam	...	...	9	...	...	...	181	181	280	273	432	530	726	231	258	137
Unfederated Malay States	...	...	...	...	...	...	...	73	114	172	159	317	334	1,156	808	296
Federated Malay States	...	...	81	75	90	95	186	249	248	288	329	567	837	391	480	257
Netherland East Indies	...	...	5	23	22	30	...	...	6	1	6	47	8	7	...	161
India(excluding Burma)	...	...	...	...	6	21	...	...	...	...	...	46	68	44	1	...
Oceania:																
Australia[4]	1,760	1,259	1,254	756	1,084	1,582	1,328	1,257	848	724	889	1,117	1,306	1,367	1,249	624
New Zealand	58	110	139	79	71	170	167	164	262	242	230	306	235	170	146	47
South America:																
Argentina	...	296	460	497	816	749	620	637	575	437	169	854	1,085	614	204	182
Bolivia	68	68	454	170	152	210	336	496	297	290	859	3,288	4,215	3,703	2,161	766
Peru	...	...	...	...	...	14	52	219	324	213	413	532	427	256	139	77
North America:																
Canada	...	...	...	...	...	75	...	15	11	...	...	[2]	[2]	15	...	...
Mexico	...	...	...	...	...	...	...	...	...	...	140	159	308	239	103	82
United States	728	842	1,488	609	1,469	1,652	1,033	1,207	1,394	898	2,116	5,373[6]	5,574[6]	4,591[6]	297	196
Europe:																
Sweden	...	...	...	...	...	...	...	...	...	...	...	...	...	3	30	5
England	175	276	327	237	382	279	270	196	197	222	360	407	255	307	177	83
France	25	18	61	112	50	30	171	229	160	145	126	162	261	45	70	23
Portugal	290	571	637	621	552	1,027	978	1,330	1,126	667	953	1,418	1,580	1,150	706	237
Spain	375	201	275	226	129	153	96	183	169	135	189	425	446	534	302	57
Italy	33	25	16	...	...	...	...	...	...	...	...	5	1	[2]	[2]	...
Austria	59	57	45	40	39	49	45	66	52	57	14	51	[7]	...	...	...
Germany	38	52	62	42	96	95	81	92	96	108	193	115	295	196	145	45
Czechoslovakia	...	...	...	...	...	...	...	...	...	...	...	[8]	[8]	[2]	70	48
Russia	...	...	...	...	...	...	...	...	...	...	...	34	126	25	5	[2]
Africa:																
Southern Rhodesia	...	...	...	...	...	...	...	...	...	...	...	2	11	37	20	17
Union of South Africa	...	8	191	36	15	...	...	...	5	...	1	2	18	37	9	...
Nigeria	...	...	...	...	...	...	...	...	...	...	...	[2]	[2]	[2]	32	...
All other countries[10]	...	...	...	15	...	...	...	9	3	5	...	8	1	2	...	...
TOTAL	3,652	3,963	5,568	3,738	5,238	6,866	6,819	8,807	8,123	7,427	10,866	20,966	25,819	31,942	14,744	11,494

[1] Data from the annual Mineral Resources of the United States Geological Survey and Bureau of Mines.
[2] Data not available.
[3] Less than one-fourth ton.
[4] Includes Tasmania.
[5] Less than one-half ton.

cent lamp filaments, though a highly important and well-known use of tungsten, do not constitute a large factor in consumption because only a ton or two of tungsten is required for 100 million lamps. The textile industry still uses a little tungsten and small quantities are used as paint pigments and for a variety of chemical, ceramic and miscellaneous purposes. Even in the aggregate, however, the consumption of tungsten for these minor uses is quite small; fully 95 and perhaps 98% of the consumption of tungsten is in the manufacture of fine steels, especially high-speed steel for metal cutting and forming operations.

SUBSTITUTES

Since tungsten is so vital a factor in the production of munitions of war as well as in the manufacture of the various metal products required in time of peace, much attention has been directed to the problem of balancing the demand against possible fluctuations of the supply of tungsten under the influence of abnormal national or international conditions. For a brief period, many years ago the United States had an indicated exportable surplus of tungsten but in recent years the demand has grown so that domestic mines, cannot now produce enough to meet the normal needs of the country. Since tungsten has always been a fairly high-priced metal the search for suitable substitutes among the cheaper metals and combinations of metals has been almost unceasing and during the World War this search was stimulated by extraordinarily high prices and by the far more insistent necessity of making up the threatened deficiency of tungsten from foreign and domestic sources.

The most discussed substitute for tungsten in high speed steel-cutting tools is molybdenum, an element found in great abundance in several localities in the United States. During the war, English and French steel makers are said to have successfully replaced about one-half of the tungsten in high-speed steel with molybdenum. One pound of molybdenum produces practically the same effect in high-speed steel as 2 or 2¼ pounds of tungsten and is normally a trifle cheaper. Steel makers, however, have had much difficulty in making a uniform melt with high percentages of molybdenum and in overcoming other problems of manufacture and as a result, while molybdenum is used in commercial steels, it replaces only a relatively small part of the tungsten. Stellite is a substitute for high-speed steel and while it contains tungsten the percentage is much smaller than in high-speed steel and pound for pound it renders more service. Other patented alloys such as "Cooperite" (zirconium-nickel) may also be substituted for tungsten tool steels and there are several good magnet steels that contain no tungsten.

As yet little real economy in the use of tungsten has been effected by the use of substitutes. Research has demonstrated that, in the unfortunate event of another war emergency, probably a 50% saving could be made in the use of tungsten in tool steels but for the present a wider use of tungsten in small percentage additions to fine steels other than high-speed steels seems to have largely offset the effects of such minor substitutions that have taken place in recent years. Substantial economy in use, however, has been brought about by designing tools in a manner such that a thin plate or tip of high-speed steel is cemented to a shank of cheaper steel. The process of "stelliting" or building up the points or wearing surfaces of tools with stellite is another factor in tungsten conservation as it permits the continued use of articles that otherwise would have to be scrapped.

OCCURRENCE

Tungsten ores are genetically associated with granitic rocks but relatively few granite masses contain tungsten, at least in workable amounts. Tungsten deposits are quite sparsely distributed throughout the world and even in individual deposits the occurrence of tungsten minerals is notoriously erratic. In several localities, float ore has been found upon the surface in some abundance and placer deposits have yielded a considerable output but as soon as these easily garnered supplies become exhausted the universal experience has been that the tungsten occurs in rather small pockets and that as these pockets and small stringers are worked out considerable time and money must be spent in seeking other enriched zones that may be irregularly distributed in the hard rock. Broadly speaking there is no tendency for tungsten deposits to "play out" in depth but as mining advances further and further below the surface prospecting becomes more and more expensive so that it often happens that the value of a new ore body does not repay the cost of finding it.

The economic significance of these geological facts is reflected in a study of the world production tables. First one country and then another has attained world leadership only to relinquish it when the flush production from new finds elsewhere discouraged the continuance of progressively more costly mining operations. Since so many properties have been abandoned before they were exhausted or merely left undeveloped, production in many countries responds fairly rapidly to the stimulus of high prices. For the last several years China has been the principal source of the world's tungsten but in 1929 when tungsten roughly trebled in price, other countries,

Concentrates containing 60% of WO_3[1]

1921	1922	1923	1924	1925	1926	1927	1928	1929		
...	...	...	...	...	19	49	54	[2]	Asia:	
[3]	14	[2]	[2]	[2]	[2]	5	161	15		Japan
2,657	3,873	4,554	3,398	6,708	7,989	5,666	8,283	[2]		Chosen (Korea)
452	112	129	150	189	92	213	211	195		China
673	1,038	960	814	849	1,634	1,277	843	[2]		Tonkin (Indo-China)
76	...	[3]	...	127	10	8	[2]	[2]		Burma and Shan States
12	258	393	214	251	234	170	139	156		Siam
60	104	41	107	174	99	22	5	351		Unfederated Malay States
80	...	10	165	27	9	22	8	10		Federated Malay States
...	...	...	...	...	...	...	...	[2]		Netherland East Indies
										India (excluding Burma)
17	44	119	75	220	99	179	238	247	Oceania:	
46	...	15	18	36	15	15	6	39		Australia[4]
										New Zealand
52	125	144	137	4	11	10	24	63	South America:	
174	9	...	[5]	82	109	79	29	1,630		Argentina
2	...	...	...	5	...	...	...	...		Bolivia
										Peru
...	...	...	...	...	...	...	...	...	North America:	
37	...	...	...	...	...	...	...	11		Canada
...	...	219	513	1,080	1,254	1,056	1,096	753		Mexico
										United States
...	...	...	...	...	...	...	...	[2]	Europe:	
81	3	2	2	1	20	12	96	27		Sweden
...	...	...	...	...	26	22	5	...		England
306	527	289	304	207	358	174	151	[2]		France
25	...	9	161	26	123	164	158	213		Portugal
7	...	1	...	...	...	...	...	[2]		Spain
...	...	...	...	...	...	...	...	...		Italy
27	42	40	13	161	...	...	...	...		Austria
35	28	28	66	60	86	78	73	78		Germany
[2]	[2]	[2]	[2]	9	22[9]	32[9]	[2]	[2]		Czechoslovakia
										Russia
17	44	...	22	22	...	33	15	28	Africa:	
...	...	...	...	...	...	...	...	...		Southern Rhodesia
...	...	...	...	...	...	...	...	...		Union of South Africa
...	...	...	...	...	...	...	...	...		Nigeria
										All other countries[10]
4,836	6,221	6,953	6,159	10,238	12,209	9,286	11,595	3,816		TOTAL

[6] Includes Alaska.
[7] 93,136 tons of ore reported mined; WO_3 content not known.
[8] Included under Austria.
[9] Year ended Sept., 30.
[10] "All other countries" includes Brazil, Chile and Norway.

notably Burma, Bolivia and Portugal, took steps to increase production and several of the tariff protected American mines were rehabilitated.

DOMESTIC PRODUCTION

As early as 1872 about one ton of tungsten ore was saved at the Charles Lane gold-silver-lead mine at Monroe, Fairfield County, Conn., but commercial production in the United States virtually dates from 1900 when 46 tons of Colorado ore were shipped to chemical works in the East. Previously some ore had been imported from England, Austria-Hungary, Germany and Australia. In the next few years the output in Colorado, Arizona, and Nevada took care of the rapidly increasing domestic demand, reaching 1640 tons in 1907. Australia, previously the principal source of world supply yielded the premier position to the United States in 1906 but by 1912, this position was taken by Burma (including the Shan States) which began producing in 1910 leaving Portugal and the United States struggling for second place. As a result of war-time prices domestic production reached a maximum of 6112 tons of 60% concentrates (equivalent) in 1918 only to drop off to 297 tons in 1919. Due to accumulated stocks and the steady influx of ore from China (which just came into production on a large scale a few months before the Armistice) the domestic mining industry was literally at a standstill in 1921 and 1922. Due to the prolonged hold-over of stocks the full effect of the tariff protection extended in 1922 has not yet been felt by domestic miners. Production in this country has advanced approximately to pre-war proportions but amounts to scarcely one-third of domestic requirements.

Table 2. Production and Average Price of Tungsten in the United States, 1900-1929.[1]

Year	Production[2] Short tons	Average Price Per unit	Year	Production[2] Short tons	Average Price Per unit
1900	46	$1.50 (?)	1915	2,332	$29.33
1901	179	2.58	1916	5,923	33.98
1902	184	3.00	1917	6,144	18.33
1903	292	2.48	1918	5,061	23.22
1904	740	4.00	1919	327	18.02
1905	803	5.57	1920	216	7.86
1906	928	6.27	1921	...	...
1907	1,640	9.05	1922	...	...
1908	671	5.72	1923	241	10.00
1909	1,619	6.32	1924	565	8.47
1910	1,821	7.62	1925	1,191	10.57
1911	1,139	5.97	1926	1,382	11.10
1912	1,330	6.28	1927	1,164	10.37
1913	1,537	7.30	1928	1,208	10.40
1914	990	7.32	1929	830	13.13

[1] Compiled from Mineral Resources of the United States, U S. Geological Survey and Bureau of Mines.

[2] Reduced to basis of 60% concentrate except 1901–1905 for which years adequate data are not obtainable.

MARKETS AND PRICES

For no particularly good reason the prices of tungsten ores are quoted per unit of tungsten trioxide (WO_3) contained. The "unit" is 1% in a ton of total material and represents either 20 pounds or 22.4 pounds of the valuable constituent, depending upon whether the short ton or long ton is referred to. In the United States the short ton unit is the basis of sales but in the United Kingdom quotations are in shillings per long ton unit. Typical ores contain 60% or 60 units of tungsten trioxide, WO_3, and must be reasonably free from certain undesirable impurities, notably antimony, arsenic, bismuth, copper, lead, nickel, phosphorus, sulphur, tin and zinc. Lower grade ores can often be sold, but only at a discount. Scheelite, the calcium tungstate mineral, since it is more readily reduced in the electric furnace, is usually quoted a little higher than wolframite and a better price can often be obtained for the pure ferberite (iron tungstate) ores of Colorado while hubnerite (manganese tungstate) ore often sells for a little less than standard wolframite (or black) ores. In short, the ores from different localities are often quoted at somewhat different prices. Attempts have been made to set up a definite scale of discounts and penalties for impurities and for off-grade ore but ordinarily the ore from a particular mine or from a particular locality is judged upon its own merits and priced accordingly, usually by the process of private negotiation between buyer and seller.

Domestic ore has always found its market in the United States. Except for relatively small sales of California scheelite to Germany before the war and sundry war time shipments, the exports of ore from the United States have been practically nil. American mines have almost never succeeded in satisfying domestic needs and the deficiency has been made up by imports. At various times there have been fairly large imports of ferrotungsten, tungsten metal powder, and tungsten steels and for a period American alloy steels and high-speed steel tools were exported in some quantity but, broadly speaking, this country has been practically self-contained as regards tungsten manufactures and has appeared in the world's markets primarily as a purchaser of ore.

Before the war, most of the world's tungsten was converted into ferrotungsten or tungsten metal powder in German ferro-alloy plants and German firms also did a considerable brokerage business in ores from all over the world. Hamburg and Berlin are still among the leading markets, purchasing ores for the large German requirements and for resale to other countries, but New York is now of at least equal importance. France and Great Britain began buying tungsten ore during the war and purchases by the ferroalloy industries in these countries, though considerably smaller than either American or German requirements have become fairly large.

The larger American producers frequently deal directly with the ferroalloy makers or the steel companies and import business for the United States is largely transacted through New York. Sales of ore are frequently made to the steel makers. Some of them use certain ores directly in the steel furnace while others arrange for converting the ore into ferrotungsten in one of the two or three domestic ferroalloy manufacturing plants. These outside plants ordinarily guarantee a minimum recovery (usually 90 to 92%) and make a fixed charge for smelting (usually 20 cents a pound of contained tungsten). In Europe the leading consuming interests are associated in what apparently amounts to a buyer's syndicate but in the United States there are no effective associations either of buyers or of sellers.

Table 2 shows the annual production and average sales prices per unit realized by domestic miners. It will be noted that in the early years prices and production both increased rapidly to meet the growing demand. In 1900 tungsten ores sold as low as $1 or $2 a unit, but by 1907 the price had risen to levels ranging from $9 to $14 a unit. The 1907-8 depression caused a reduction to $5 but late in 1908 prices were better and the domestic output responded to an active demand, the recovery being assisted by the decline in production from Australia. Another depression in the steel industry and a sudden influx of supplies from Burma caused a setback in 1911 but the growing use of tungsten sustained the industry until early in 1914 when demand slackened and prices sagged to about $6.50 a unit. During the second quarter of 1915 war orders began to call for abnormal amounts of high-speed steel tools and as the British Government embargo cut off supplies of ore from Burma and other British possessions, prices soared rapidly to $50 and then to $62.50 a unit. The boom reached its climax early in 1916 when $82.50 and in at least one case $100 a unit, was paid for ore.

Before long the prices dropped again to around $17 but in 1918, notwithstanding the arrival of heavy shipments of Chinese ore, good domestic ore was worth $25 or more. After the Armistice, Chinese ore dominated the market and despite the general industrial activity high-grade tungsten ores were worth only $7 a unit in 1920. Even before the 1921 depression the domestic tungsten industry collapsed and during the discussion preceding the passage of the Tariff Act of 1922 business was largely speculative as consumers were overstocked. The 1922 tariff (45 cents a pound on the tungsten contents of ore) was equivalent to an addition of $7.14 a unit but world prices having declined far below the pre-war average domestic miners were able to get only about $10 a unit for their product until 1929 when a sharp upturn brought the price above $15. Lack of buying resulted in a heavy market in 1930. The new tariff, effective in June, increased the duty on ore to $7.93 a unit (50 cents a pound of metal content) and encouraged a little speculative importation early in the year but consumptive demand in the United States was practically at a standstill and European purchases were insufficient to sustain the outside market. On December first, Nelson Franklin, the well-known tungsten authority, estimated the market for wolframite at $12.50 and for domestic scheelite or ferberite at $13 a unit. Ferrotungsten was nominal at $1.10 to $1.15 a pound of tungsten contained and tungsten powder, 98%, was quoted at $1.70 a pound.

EFFECT OF STOCKS

In the early years of the tungsten industry the fundamental relations between supply and demand and price were fairly evident. In harmony with elementary economic law prices rose with demand and were held in check by the advent of production from new fields. Since 1918, however, the situation has been obscured by the existence of accumulated stocks. Most of these stocks are difficult to evaluate. Data as to tonnages in bonded warehouses, awaiting liquidation, are, of course, easily obtained and there is reason to believe that the stocks of ore in private warehouses and in consumers' hands, a dominant factor in the situation for some years after the Armistice, have at last dwindled to normal proportions, except for fairly heavy domestic purchases in 1929 and 1930 anticipatory of the tariff increase. At the present time the uncertain factor is the accumulated supply of high-speed steel scrap which is used over and over again in the manufacture of tungsten steels. Most of the tool steel companies agree regularly to buy back high-speed steel scrap from their customers and due to the relatively high price of such steels the percentage of salvage is greatly higher than that of ordinary tonnage steels. While the loss of tungsten in melting turnings and similar light scrap is comparatively high even such material can usually be sold back to the steel makers at prices that justify the expense of segregating it from cheaper grades of scrap. As the use of tungsten steels continues and as the use of high-speed steel extends to heavier tools, such as dies, the importance of this revolving fund of tungsten in the form of scrap tends to become progressively greater. Opinions vary as to the actual quantity of new tungsten that is annually displaced by the re-use of scrap but it is probably not far from 25% of the total and in periods of reduced demand such as during the greater part of the past year, it may be somewhat more.

Table 3. Imports vs. Production of Tungsten in the United States, in Short Tons, 1912-1929

		IMPORTS		TOTAL SUPPLIES[1]			
Year	Domestic[1] Production	Ore	Tungsten and Ferro-Tungsten	Total Equivalent[1,2]	Less[3] Exports	Supplies[1]	% Imported
1912	1,330	824	323	1,620	...	2,950	55.0
1913	1,537	449	740	2,150	...	3,690	58.3
1914	990	299	218	815	...	1,805	45.1
1915	2,332	1,776	8	1,940	...	4,270	45.4
1916	5,923	4,072	43	4,520	645	9,800	46.1
1917	6,144	4,879	1	5,310	2,615	8,840	60.1
1918	5,061	11,609	...	12,855	1,385	16,530	77.8
1919	327	9,408	198	10,915	45	11,195	97.5
1920	216	1,949	999	4,415	5	4,625	95.5
1921	...	1,614	253	2,370	...	2,370	100.0
1922	...	1,865	534	3,300	...	3,300	100.0
1923	241	....	40[4]	90	5	325	27.7
1924	565	....	71[4]	165	5	725	22.8
1925	1,191	710	420[4]	1,675	15	2,850	58.8
1926	1,382	2,110	175[4]	2,510	35	3,855	65.1
1927	1,164	1,810	14[4]	1,840	20	2,985	61.6
1928	1,208	2,380	56[4]	2,510	20	3,700	67.8
1929	830	4,980	236[4]	5,525	115	6,240	88.5

[1] Calculated into short tons of 60% concentrate.
[2] Chinese ore imported prior to 1922 considered as carrying 65% WO_3 and tungsten and ferrotungsten considered as equivalent to 2.25 times their gross weight in ore carrying 60% WO_3. Much of the ferroalloy imported is made into tungsten steel which is exported (with benefit of drawback of 99% of the duties) but such imports are herein included.
[3] Ore equivalent of tungsten and ferrotungsten and tungsten wire exported; exports of ore negligible.
[4] Actual tungsten contents (calculated into ore for next column by multiplying by 2.3).

Table 4. International Balance Sheet of Tungsten

(Estimated normal supply[1] and probable maximum demand by countries in terms of concentrates containing 60% WO_3)

SUPPLY			DEMAND		
Country	Short Tons 60% WO_3	% of Total	Country	Short Tons 60% WO_3	% of Total
China	8,000	57	United States	4,000	29
Burma	2,000	14	Germany	4,000	29
Bolivia	1,500	10.5	Great Britain	3,000	21
United States	1,500	10.5	France	2,000	14
Portugal	250	2	Others	1,000	7
Australia	250	2			
Others	500	4			
Total	14,000	100	Total	14,000	100

[1] At international prices (exclusive of U. S. duty) of $5 to $10 per short ton unit.

SOURCES OF NEW SUPPLIES

China has dominated the world situation for about 12 years. The first flush production from the newly opened fields, extending into the post-war readjustment period, flooded the world's markets and, in succeeding years, as the flow of supplies continued in fair volume, prices dropped to the point where producers in other parts of the world were forced to suspend operations. As stocks were gradually dissipated Chinese exports again increased in volume—in 1928 they amounted to 8283 metric tons—but as demand increased even faster than supply it was deemed desirable to boost the price from $3 to $4 per unit, the prevailing price for several years, to $8 or more in 1929. This increase, combined with certain political changes affecting the Chinese-American group of dealers that had previously enjoyed a practical monopoly of sales, encouraged the revival of tungsten mining in other countries. The Chinese situation is still very much clouded and information is not at hand as to whether it will be controlled henceforth in Europe or in the United States. There is reason to believe, however, that when general industrial activity comes back to normal the demand for tungsten will exceed the present capacity of China to produce and that world prices will tend to become stabilized at a figure that will permit profitable operations, on a moderately large scale at least, in Bolivia, Burma, Portugal, and (with tariff protection) the United States.

◆ ◆ ◆

Dr. L. W. Bass Joins the Borden Company

Dr. Lawrence Wade Bass, who, for two years, has been a member of the Executive Staff of Mellon Institute of Industrial Research, Pittsburgh, Pa., has resigned, effective February 1, to accept the post of Assistant Director of Research of the Borden Company, New York, N. Y.

STRUCTURAL METALLOGRAPHY

By H. B. Pulsifer*

SURFACING AND ETCHING

SMOOTHING and etching, together, form one of the main operations in metallographic science. And smoothing and polishing, alone, often complete the preparation of a sample for microscopic determination of inclusions and defects. As to just how all of this finishing shall be done admits of wide variation.

The pioneers in metallography, Sorby, Osmond, Martens, Stead and others, naturally used hand polishing on papers and stretched fabrics but they did not fail to attempt shortening the time and lessening the labor by the use of swiftly rotating wheels. Finishing on wheels has thus been in use for some thirty years and there has been continual effort to perfect the technique and make the operation purely mechanical and automatic. The elaboration of the fabric and abrasive has often been complicated to the point of impracticability while the numerous machines on the market are very well described in the circulars freely distributed by the makers.

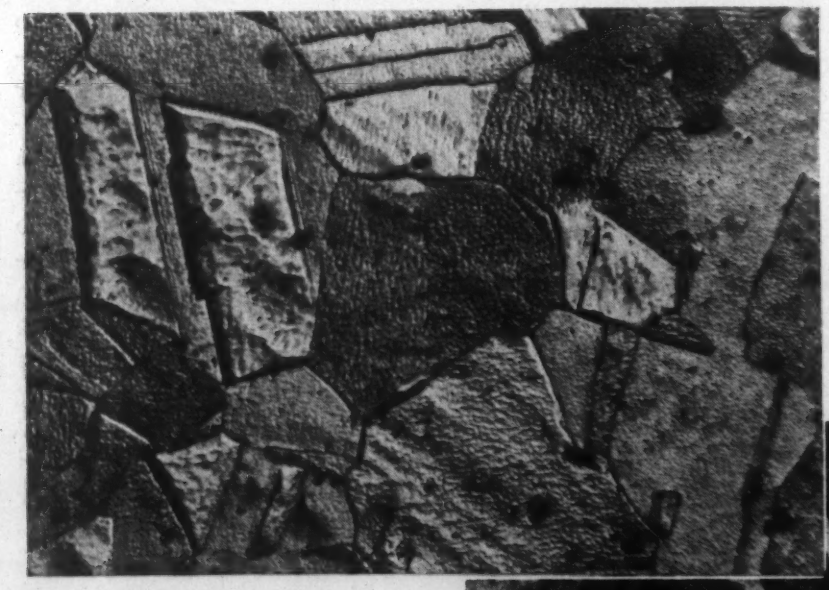


Fig. 1.—Hot-Rolled Copper Rod Etched with Conc. NH_4OH + H_2O_2 (30%). Magnification 500×

Fig. 2.—Annealed Monel Wire. Longitudinal. Etched with Acetone-Nitric-Acetic Solution (50-50-20). Magnification 100×

Fig. 3.—Annealed Monel Wire. Longitudinal. Etched with Conc. HNO_3 + CrO_3. Magnification 200×

Certain factors inherent in the use of machines led the author to abandon their use several years ago. These adverse conditions were: cost, upkeep, crowning of the specimen and inability to remove scratches. The results that have been attained have already been published in three technical papers.** But with more practice and continual inquisitiveness regarding minor details better prints are made both quicker and easier.

The three major improvements that have been personally developed without direct copying from previous workers are based on the three following observations:

1. Damp carborundum powder heaped on a hand board is a very fast smoother. The finest commercial powder is repeatedly suspended and finally settled for use.
2. Slightly etched surfaces finish quicker and with a softer abrasive than by continued rubbing alone.
3. Many granular surfaces can be finished, that is, chemically cleared and etched, by etching in the proper reagent. Polishing by mechanical means is omitted.

In a simple case the procedure may be carried out in the following steps. The specimen is supposed to have been finished to a single flat facet on a file with at least 32 teeth to the inch. With materials too hard to file the equivalent of file smoothing can be done on grinding wheels or emery papers.

1. Rub on No. 0 coarse emery paper laid on plate glass. (Fifty rapid passes often suffice.)
2. Rub on No. 0 fine emery paper laid on plate glass. (Again 50 passes may be sufficient.)
3. Rub on No. 000 fine emery paper on plate glass. (A hundred rapid passes finishes many materials.)
4. Rub with some 50 passes on damp carborundum on hand board.
5. Rub with some 100 passes on damp tripoli on hand board.
6. Agitate in etchant. Specimen is held with tongs. Rinse, dry.
7. Place on microscope and photograph.

The total time required for the first six steps may be as short as 60 seconds in some cases. With some materials certain omissions and abbreviations are possible. With other materials two or three minutes are inevitably consumed. Still other materials, best finished by light etching and repolishing before final etching, need four or five minutes.

There is very great variation in the response of metals

* Metallurgist, Cleveland, Ohio.

** Microscopic Structure of Copper. *Transactions American Institute of Mining & Metallurgical Enginners*, Vol. 73 (1926) page 707. Magnesium—Its Etching and Structure. *Proceedings Institute of Metals Division, American Institute of Mining & Metallurgical Engineers* (1928) page 461. Smoothing and Etching of Cupronickel, Bronze, Brass and Steel. *Transactions Institute of Metals Division, American Institute of Mining & Metallurgical Enginers* (1929) page 291.

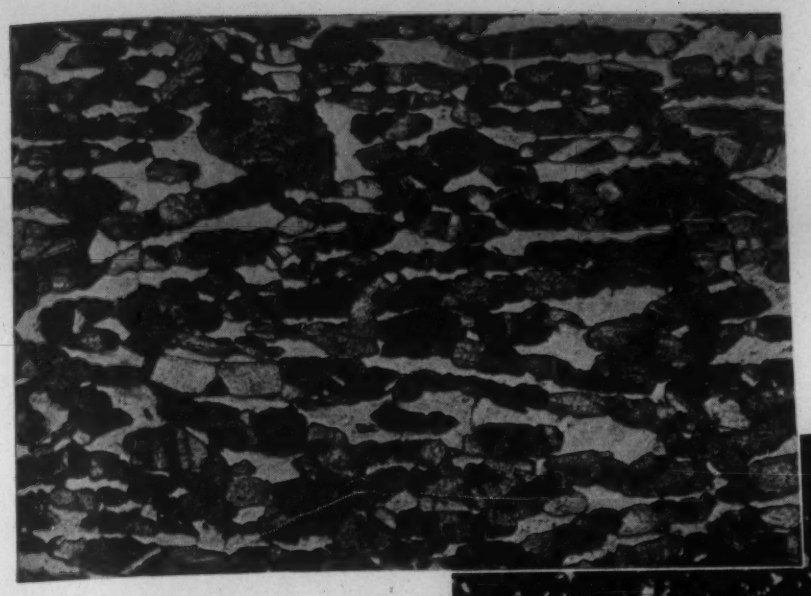


Fig. 4.—Tobin Bronze Wire. Annealed. Longitudinal. Etched in Conc. $HNO_3 + CrO_3$. Magnification 100×

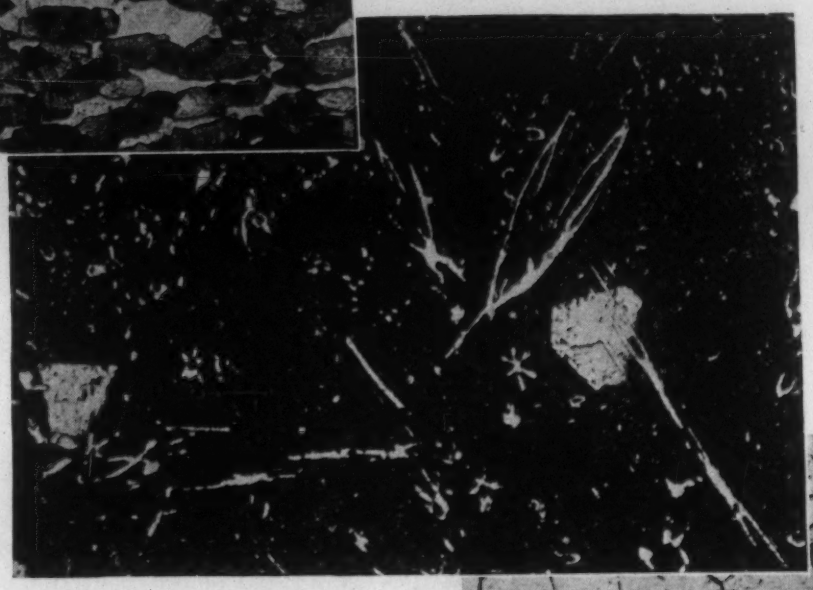


Fig. 5.—Babbitt Metal. Smoothed on Tripoli and Dipped in Acid $FeCl_3$ Sol. Magnification 200×

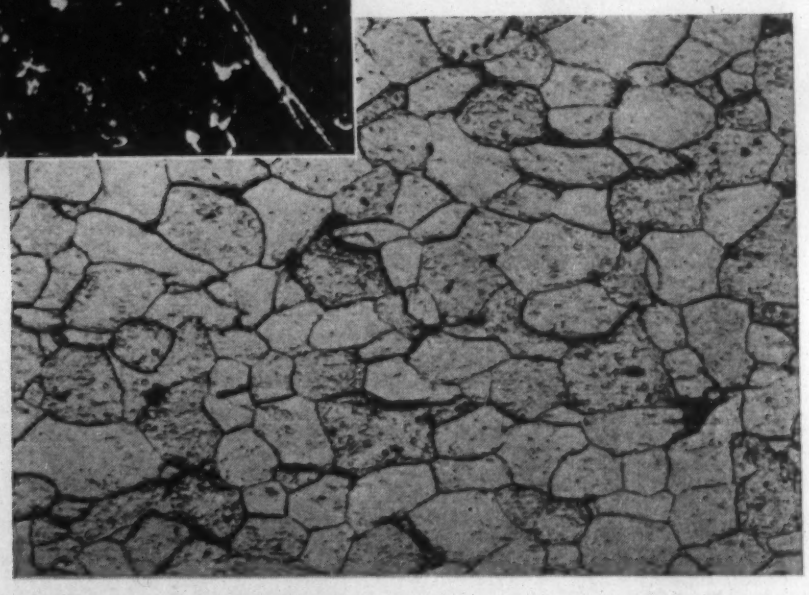


Fig. 6.—Low-Carbon Steel Wire. Longitudinal. Repolished and Etched with "Picnihol." Magnification 200×

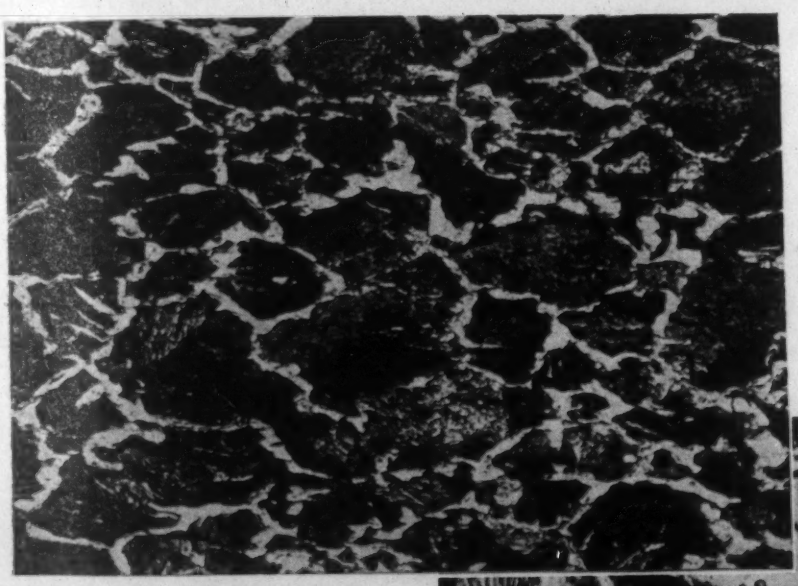


Fig. 7.—Steel Wire. 0.45% Carbon. Longitudinal. Repolished and Etched with "Picnihol." Magnification 200×

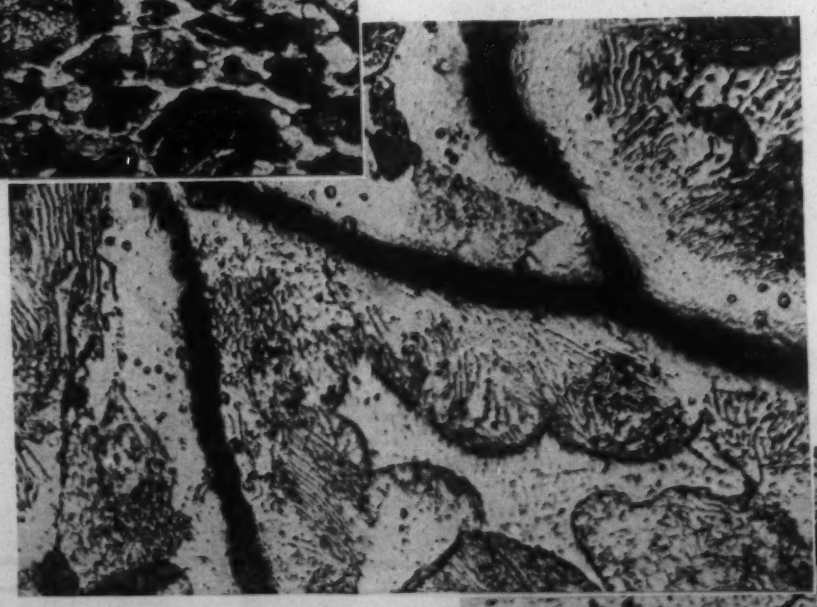


Fig. 8.—Cast Iron (Machinery). Etched with "Picnihol." Magnification 500×

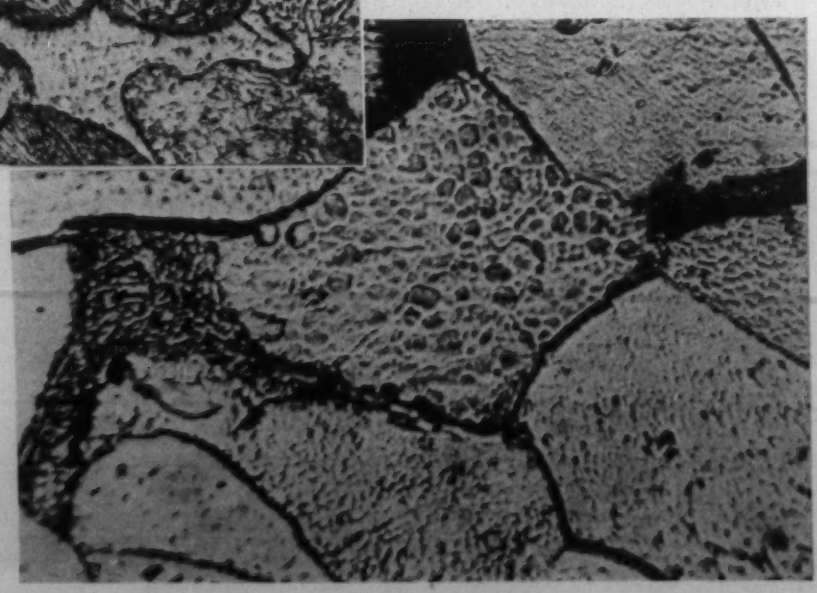


Fig. 9.—Low-Carbon Steel Wire. Longitudinal. Etched with "Picnihol." Magnification 1000×

preclude the finding of the wonderful results of an optimum immersion in the reagent.

Fig. 1 shows the structure of a hot-rolled pure copper at 500 diameters as etched with concentrated ammonia containing a little 30% hydrogen peroxide. The granular surface was entirely cleaned off and the crystal put in high relief with only slight pitting.

Fig. 2 shows the structure of an annealed Monel wire as etched in acetone-nitric-acetic reagent to clear the surface and outline the crystals. This print is at 100 diameters magnification.

Fig. 3 shows a similar Monel wire at 200 diameters after etching in concentrated nitric acid containing solid chromic anhydride. This latter reagent etches more passively and pits much less than the acetone-nitric-acetic reagent.

Fig. 4 shows a Tobin bronze wire at 100 diameters with the β-component bright after etching in concentrated nitric con-

and alloys to rubbing on papers. If a surface roughens instead of smooths it may be necessary to wet the paper with carbon tetrachloride or other liquid. There is also a certain "touch" or skill in pressure, speed and control requisite for fast and excellent results. But this is a small matter of practice and adaptation. The above direct procedure applies to many sorts of copper, brass, bronze, nickel brasses, Monel, zinc, babbitts, aluminum and its alloys and magnesium and its alloys. With a light etching, repolish, and final etching most of the ferrous materials are included.

The choice and use of a suitable etchant is the critical step in this sort of finishing. The reagent must dissolve the granular surface debris and simultaneously outline the structure. It must not pit the specimen. The range of the echant must be discovered by risking the ruin of specimens to discover limits and effects. Unwillingness to destroy a surface may

taining chromic anhydride. A fresh solution will produce this effect while a used solution is more apt to etch with hair-fine boundaries and all units smooth and glassy.

Fig. 5 shows a high grade babbitt that was given a granular finish on tripoli and momentarily dipped in acid ferric chloride solution.

Since most of the ferrous alloys contain components of enormously different solution rates the quickest way to finish them appears to be with short rubbing on tripoli, etch slightly, again smooth on the tripoli and give a final short etch in a mixture of picric and nitric acids in alcohol. Very fine results can be obtained quickly by repeating the repolish and etch several times.

Fig. 6 is a low-carbon steel wire at 200 diameters finished in this way. Fig. 7 is a 0.45% carbon wire, also at 200 diameters. Fig. 8 is a piece of ordinary machinery cast iron at 500 diameters finished similarly.

Some effort has been made to gain a smoother surface than can be made by finishing on tripoli. Thus rouge and "shamva" easily finish to a much smoother surface but almost inevitably leave scratches that seriously mar any print. The suspension and settling of these substances somewhat reduces their scratchiness but has not yet been found to be entirely satisfactory. Although it appears almost certain that this step can be improved with adequate research the shorter finishing may be found adequate for many purposes.

The value of photomicrographs is greatly enhanced by having large fields. The very flat surfaces obtained by the short hand rubbing method enables prints like those above to be cut from near the corners of 8 × 10-inch prints. Fig. 17 is one of these contact prints.

When inclusions alone are being looked for the surface as finished on tripoli after a light etching is often in suitable condition. A final glossier surface can be made by rubbing on washed rouge or "shamva," or similar material. But there may then appear a crop of new sharp scratches.

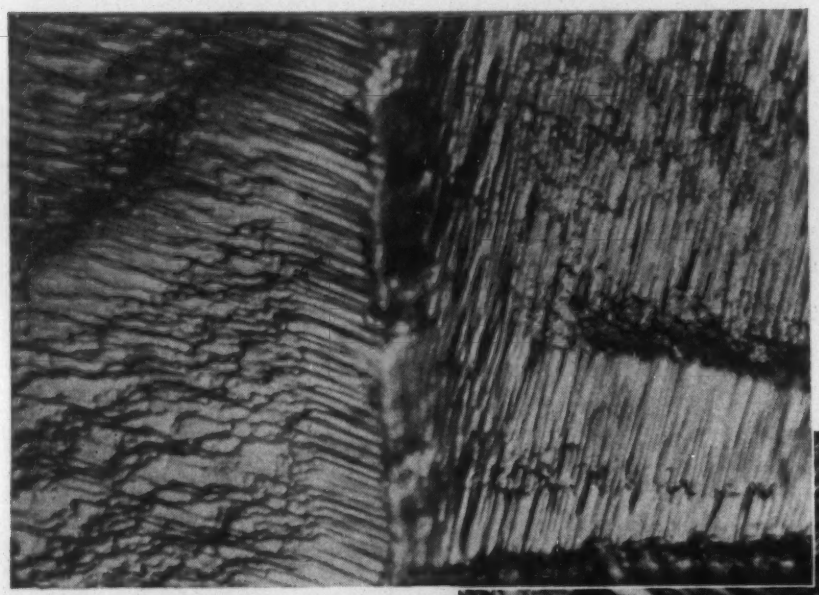


Fig. 10.—Grain Boundary in Annealed Copper. Etched with Conc. NH_4OH + H_2O_2 and Dipped in Conc. HNO_3. Magnification 1500×

Fig. 11.—Cold-Drawn Copper Wire. Longitudinal. Etched with Conc. NH_4OH + H_2O_2 and Dipped in Conc. HNO_3. Magnification 1500×

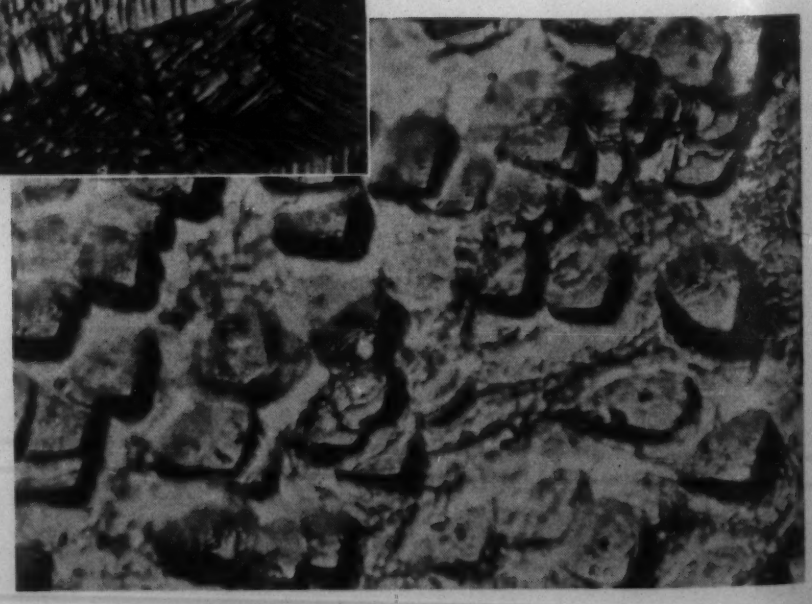


Fig. 12.—Fine-Structure of Meteorite. Etched in Sol. of 50 Parts Acetone, 50 Parts Conc. HNO_3 and 20 Parts Glacial Acetic Acids. Magnification 1000×

ETCHING REAGENTS

If a metal surface is to be cleared of its external coating of granular or cold-worked smear from the smoothing the reagent must first dissolve this layer. Then the metal should become passive with the structural details exposed. Concentrated nitric acid, chromic anhydride and hydrogen peroxide apparently favor this type of attack. It may easily happen that more suitable reagents or combinations will be found.

The entire mechanism of the finishing is different from giving a polished surface and a delicate etch to outline demarcations with unaffected exterior crystal surfaces. As by a magical touch the originally granular or microscopically rough surface transforms into a finished design. Experiments will demonstrate that this almost unbelievable result can be attained.

TABLE OF ETCHING REAGENTS

Reagent	*Material*
Concentrated nitric acid and chromic anhydride (quenched in alcohol)	Copper, brass, bronze, Monel
Concentrated ammonia containing hydrogen peroxide	Copper
Picric and nitric acids in alcohol, "picnihol"	Ferrous alloys
Citric, tartaric, malic acids, 50% solutions, or concentrated	Magnesium and alloys
Palmerton reagent	Zinc per cent alloys
Acid ferric chloride solution	Babbitts, tin
Dilute aqua regia containing hydrogen peroxide, or aqua regia in glycerine	Stainless ferrous alloys
Solution of 50 parts acetone, 50 parts conc. nitric, 20 parts glacial acetic acids	Nickel and alloys, chromium steels, high speed steels

With the interesting results already obtained one can easily believe that intelligent and systematic research will be able to greatly develop this type of finishing metallographic specimens.

METAL FINE-STRUCTURE

The so-called "grains," or crystals, in metal are actually sheaves or packets of much smaller units all similarly oriented. A light or passive etch hardly reveals a trace of them but they appear on deep etching. Figs. 2 and 3 are typical of "active" and "passive" echants, respectively. The disclosure of fine-structure in Fig. 2 causes the "coloring." No trace of it appears in Fig. 3.

The development of this fine-structure is not significant in current metallographic science. From the grosser microscopic structures we have a short-cut to atomic arrangements and dimensions. However, since this fine-structure unquestionably comes into play in all the physical and chemical properties of metal, eminently so in cold-working, its study should offer a fertile field for research.

The lack of more knowledge of the fine-structure can be attributed directly to the prevailing custom of smooth mechanical polishing and faint etching. Otherwise the curious "etch-figures" occasionally revealed would long ago have received systematic study. One author has recently stated

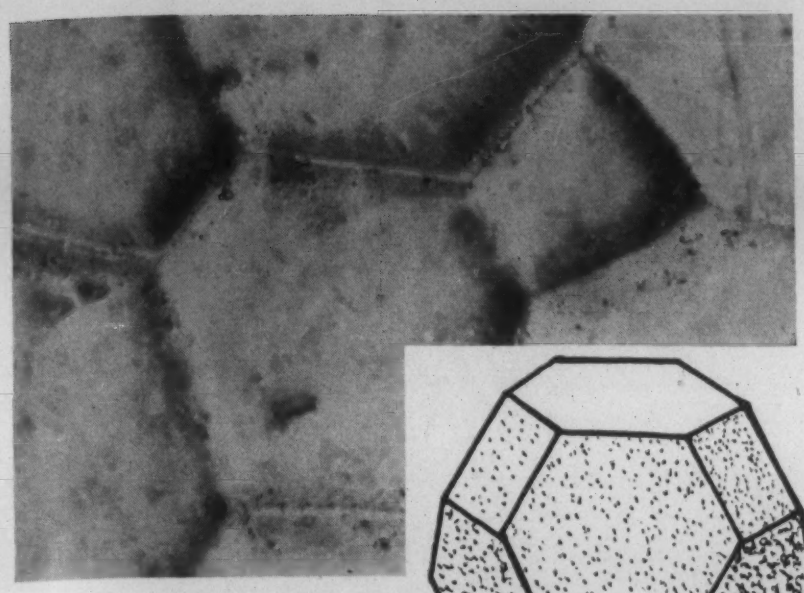


Fig. 13.—Hot-Extruded Magnesium. Etched with H_2SO_4 in Acetone. The Square and Hexagon. Magnification 1000×

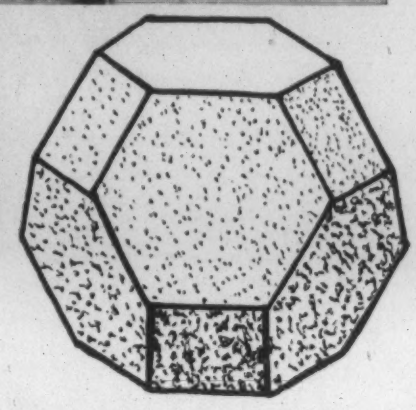


Fig. 14.—The Tetrakaidecahedron

that these "etch-figures" may be found in cast and coarse-grained metal but not in worked metal.

The appearance of the fine-structure has already been shown at low magnifications in Figs. 1 and 2 in copper and Monel but is barely hinted at in Fig. 6, a low-carbon steel. To demonstrate this finer structure in ferrite we have but to show the same material with a deeper etch and a higher magnification. This is done in Fig. 9 at 1000 diameters. The central crystal is plainly a mass of smaller units, not all of equal size.

But this appearance of the smaller units which can always be disclosed in the ferritic materials is also found in all other metals and alloys. It is very easy to portray in copper, the brasses and bronzes. Fig. 10 shows a grain boundary in pure annealed copper at 1500 diameters. The two series of parallel, missed lamellae are seen on either side of the border. Fig. 11 is also at 1500 diameters and shows the flow-structure in a section of cold-drawn pure copper wire. For lack of a more suitable name these fine units might be called "crystimes."

The appearance of these crystimes doubtlessly depends greatly on the orientation of the crystal surface exposed, as well as on the echant. Their delineation is obviously a much finer and more delicate operation than exposing grain boundaries. When metal is etched passively they fail to appear. Like massed troops, they may have quite different outlines depending on the point of view. And, as massed troops may spring into different formations, depending on the order of command, it is likely that they will show different outlines, depending on the kind and concentration of the etching reagent.

One of the startling disclosures frequently seen in the deeper etching of many materials is appearance of enormously large crystimes. They might be called "crystones." Space precludes offering prints of these strange sub-crystals, giant microstructures, except in the case of a section from the San Angelo meteorite that was examined some time ago. From out of the iron-nickel groundmass when etched in the acetone-nitric-acetic reagent appeared in certain spots the crystones shown in Fig. 12 at 1000 diameters. These dominant crystallites appeared merely as roughened spots at 100 diameters, but, fortunately, happened to be looked at more closely with the 4 mm. objective. They are similar to crystones frequently seen in copper, magnesium and ferrite.

It is true that, as yet, the author has commonly found these units only in cast metal. That they are absent from worked and recrystallized metal would be a wholly unwarranted conclusion. They are only casual appearances, never having been diligently looked for in any material. There is also the condition that they may have a much better chance to form in cast metal, compared with the limited time and latitude possible in the recrystallization of worked metal.

TETRAKAIDECAHEDRA

The forbidding word "tetrakaidecahedron" simply means a truncated regular octahedron. For some years the biologists have recognized its form in plant cells. It is a surface tension formation, being merely that geometric form that can be close-packed with minimum exposed surface. In its regular form it has eight hexagonal sides and six square sides. Under the hazards of unit growth in recrystallized metal squares and hexagons should be prominent figures with the *average* number of sides close to six. A typical average section will show many squares surrounded by larger hexagons, the squares smaller than the hexagons.

After once noticing the typical conventionalized pansy outline seen in Fig. 15 the figure, or its approximation, will be seen in many grain sections. In cast metals the units will likely be too large to appear characteristically on micro-sections. In many wrought and recrystallized materials they will be seriously interfered with or too small to recognize. Formations assuming characteristic crystal outlines, like the units in Fig. 5, or growths from twin fragments, common in copper and brasses will hardly assume this surface tension shape.

But the characteristic shapes appear prominently in magnesium, β-brasses, high-chromium δ-ferrite austenite, pure tin and in many other alloys. A splendid example is from hot-extruded magnesium and seen in Fig. 15 at 1000 diameters. Unfortunately, only one quadrilateral and one hexagon can appear on the small print. Another print, Fig. 16, which is δ-chromium-ferrite at 100 diameters shows one unit surrounded by four larger polyhedra. It takes only a little imagination to pick out six or eight conventional tetra-pansies in Fig. 6, which we have already learned is a low-carbon steel.

A grain count of 280 crystals on one print of hot-extruded magnesium gave the average number of grains touching each unit to be 5.91. A count of similar surrounding grains on one print containing 201 crystals of δ-chromium-ferrite was 5.97. In each case the sides touching were as follows:

Magnesium										
Number of grains touching	3	4	5	6	7	8	9	10	11	12
Number of grains.....	5	39	82	71	43	25	9	4	..	2 = 280

Average touching grains = 5.91

Chromium-ferrite										
Number of grains touching...	3	4	5	6	7	8	9	10	11	
Number of grains.....	1	21	59	57	38	21	1	1	2 = 201	

Average touching grains = 5.97

The approximated tetrakaidecahedron thus appears as a widely distributed crystal form in the metal realm. This happens when surface tension plays a prominent or dominant part in determining crystal shape. It would not be surprising to find this surface tension necessity extending to determine the shape of sub-crystal units, the crystones.

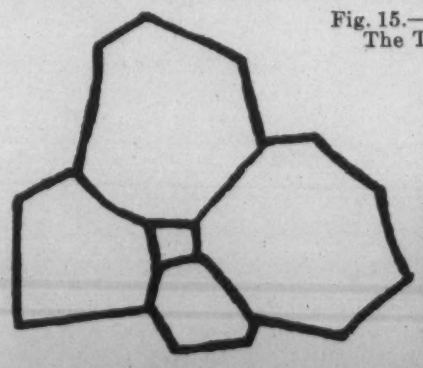
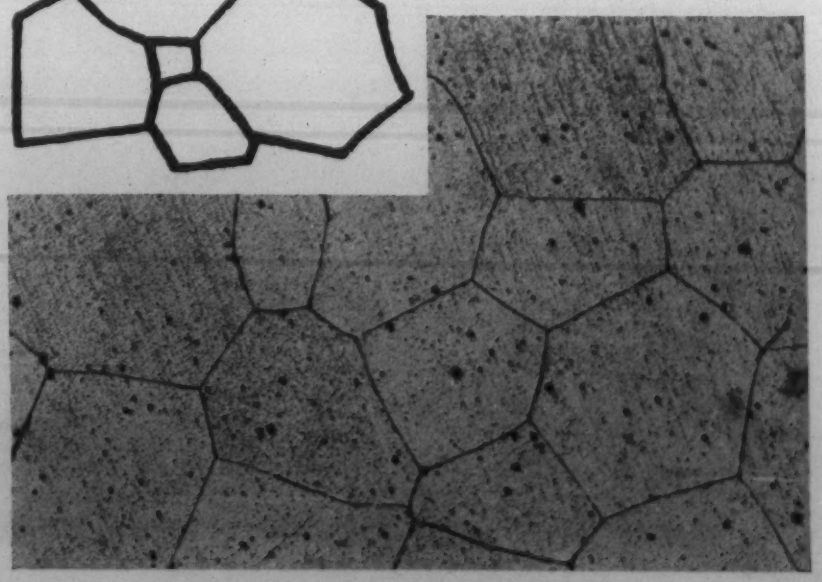


Fig. 15.—Typical Section in Metal. The Tetra-Pansy. (Traced)

Fig. 16.—Typical Polygons of Quenched Delta-Ferrite in 18% Cr-Iron. Etched with Dil. Aqua Regia + H_2O_2. Magnification 100×



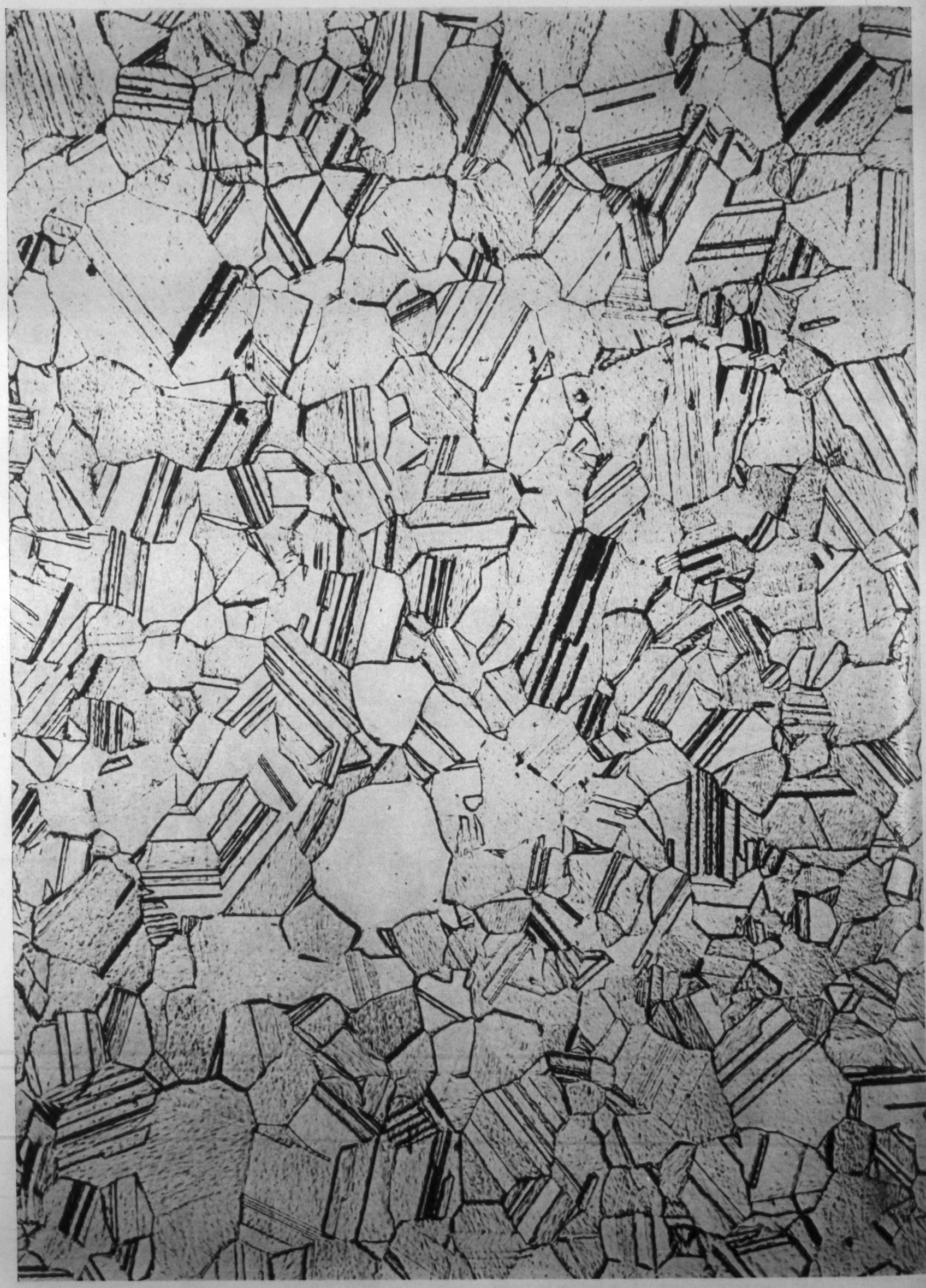


Fig. 17.—"Duronze." Annealed Wire Etched with Conc. HNO_3 + CrO_3 After Smoothing on Tripoli. Magnification 250×

An Automatic Metallographic Polishing Machine

By W. F Davidson*

The interest shown by engineers who have seen the automatic metallographic polishing machine used by the Research Bureau of the Brooklyn Edison Company has suggested that it is of sufficient value to justify description.

In order that the basis on which it was developed may be understood, it is desirable that statement be made of the various controlling considerations. The laboratory handles special investigations of widely divergent types and does only a small amount of routine work. Materials for microscopic examination range from brass condenser tubes and lead cable sheath to alloy steels for high temperature service. Frequently it is necessary to examine specimens at the edges or in the vicinity of fracture. All of these considerations taken together mean that the work is rather different from that met with in a laboratory handling large numbers of specimens of essentially uniform type.

The frequent necessity of examining specimens at the edges and the fact that many are of such shape as to make holding difficult, during grinding and polishing combined to dictate some method of mounting. The familiarity with electrical insulating materials suggested at once that Bakelite molding compound would probably meet the various requirements. It can be obtained in several degrees of hardness and is generally resistant to the various etching reagents. Furthermore, it will hold most types of metal in a rigid manner. A simple mold, as shown in the photographs, was constructed in the shop and arranged for use in a small laboratory press, which is fitted with electrically heated hot-plates. Molding is usually done at 275°F. and 5000 lbs./in.^{2} pressure, but these figures may be modified to suit individual requirements. For mounting brass and other materials of similar hardness black Bakelite AM-120 has been found very satisfactory, while for steel and hard materials black Bakelite AM-261 gives a more satisfactory surface.

In order to secure specimens of uniform height, the quantity of molding material must be adjusted to the size of the specimen. This is done very easily by determining the volume of the specimen by placing it in a graduate partly filled with water and then reading from a chart the proper weight of molding compound.

This method of mounting has fulfilled all expectations. In addition to permitting molding odd shaped specimens in convenient form for grinding and providing sufficient support to the edges to permit polishing to the limits of the specimen without rounding the corners, it is of value in mounting specimens such as sections of condenser tube where it is essential that they should not be deformed in the polishing process. A further advantage is sometimes realized when specimens are placed on the microscope stage where the smooth face of Bakelite permits shifting about without seriously disturbing focus or danger of scratching expensive lenses. No difficulty has been experienced as a result of the action of etching solutions, even where it is necessary to re-polish and etch several times.

On several occasions thought had been given to the use of an automatic polishing machine to insure greater uniformity and eliminate some of the time-consuming operations of hand polishing. Magnetic chucks for holding specimens were clearly out of the question and suitable alternative means had not been suggested. However, with the development of the Bakelite mounting this difficulty was overcome and the remaining obstacles did not appear to be serious.

In designing the machine it was considered essential to avoid the use of gears or intricate mechanical parts near the specimen and to plan the mechanism so that it could be dismantled readily and cleaned to insure removing all traces of grit which might shake down and injure the surface of the specimen. Furthermore, it appeared imperative to hold a specimen so as to allow some freedom for self-alignment on the polishing disc and at the same time prevent any tendency to tip or roll. The machine as constructed is shown in the accompanying photographs. The small motor with built-in worm gear reduction unit drives a second worm gear attached to a crank disc with vertical shaft. The speed of the crank shaft is about 11 r. p. m. and the throw is adjustable to meet individual requirements. A rigid steel arm of channel section extends over the polishing head and is oscillated back and forth by the crank disc. A specimen holder fits into a carefully made bearing on the end of the arm and holds the specimen by four hardened steel fingers, which have small pads just above the surface of the polishing disc. These fingers fit into grooves molded in the side of the specimen, while a pin with interchangeable weights extends through the center of the shaft into a hemispherical recess in the top of the specimen. By adjusting the weights, the pressure on the polishing disc may be kept at any desired value while the arrangement of the fingers eliminates any tendency to tip or roll. For rotating the specimen a cord with spring tension device is attached to two stationary arms and passes around a grooved pulley on the shaft of the specimen holder. As the arm swings back and forth, the pulley is rotated to an extent controlled by the spacing between the shaft arms. In operation it is found that there is a small amount of slippage and the specimen turns more in one direction of rotation than the other. This leads to the very desirable feature of eliminating exact repetition and so gives added insurance of uniform polishing.

The entire polishing unit is mounted on a hinged base so that it can be swung back without difficulty for inserting specimens or changing polishing discs. Needless to say, it is necessary that the parts be carefully aligned so as to insure movement of the polishing arm in a plane parallel to the disc and with the specimen holder always at right angles to the discs.

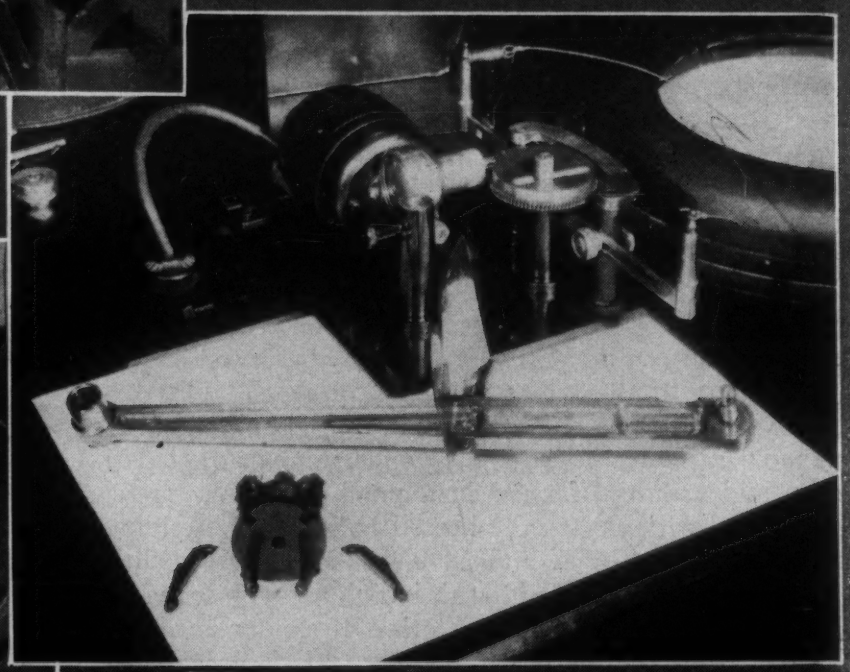
As will be noted, the details have been worked out in such a way as to permit ready dismantling for cleaning. No tools are necessary and it is only a matter of a few minutes to remove all traces of old polishing compound. Gold-plating of parts has been helpful in permitting cleaning by chemical means.

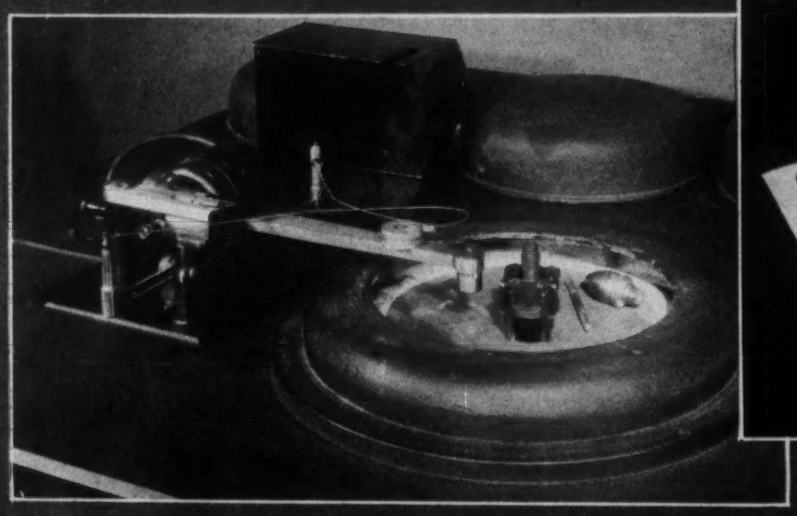
It is usual practice to carry on the first stages of grinding by hand and to use the machine only for polishing on the cloth discs. With this procedure, it is possible to keep several specimens in progress at the same time, as while the machine is finishing one, another can be etched and given preliminary examination under the microscope. In addition, the uniformity of results obtained on a series of similar samples may be extremely valuable in affording a better basis for exact comparison of photomicrographs.

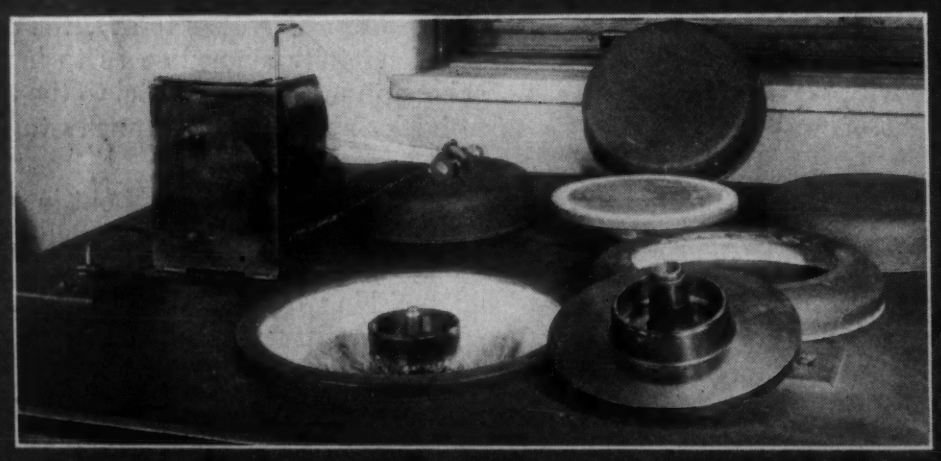
Many obvious modifications of the general scheme suggest themselves. For a battery of polishing machines it would be a simple matter to use a single oscillating motor and driving device with one arm and specimen holder for each disc. It might also be possible to drive the oscillator from the same source as the polishing disc, but this makes it a little more difficult to secure independent adjustments of speed as can be done with present arrangements. For some types of polishing fluid, considerable labor can be saved by the use of air agitated bottles as suggested in the photographs.

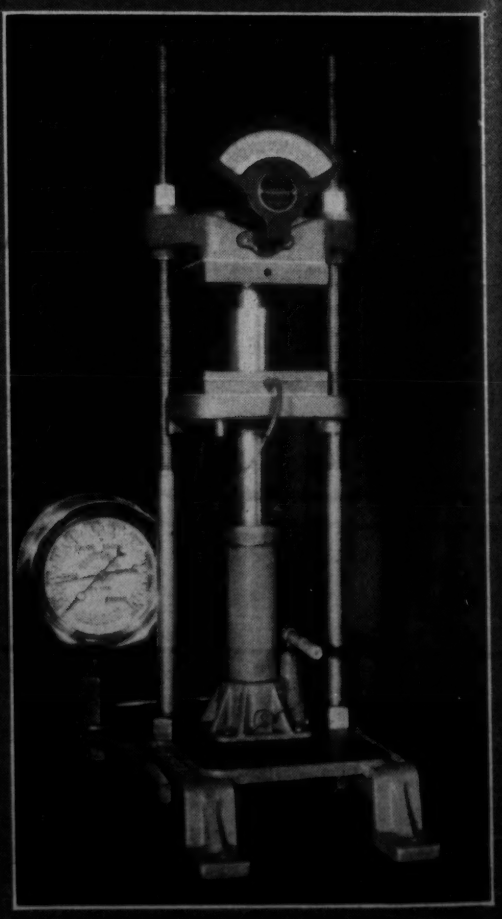
* Director of Research, Brooklyn Edison Co., Inc.

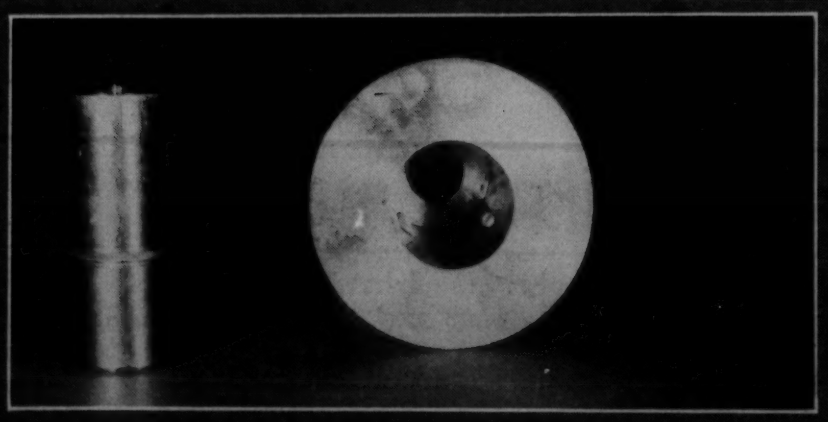
VIEWS OF POLISHING MACHINE, MOLD FOR BAKELITE MOUNTINGS AND MOLDING PRESS

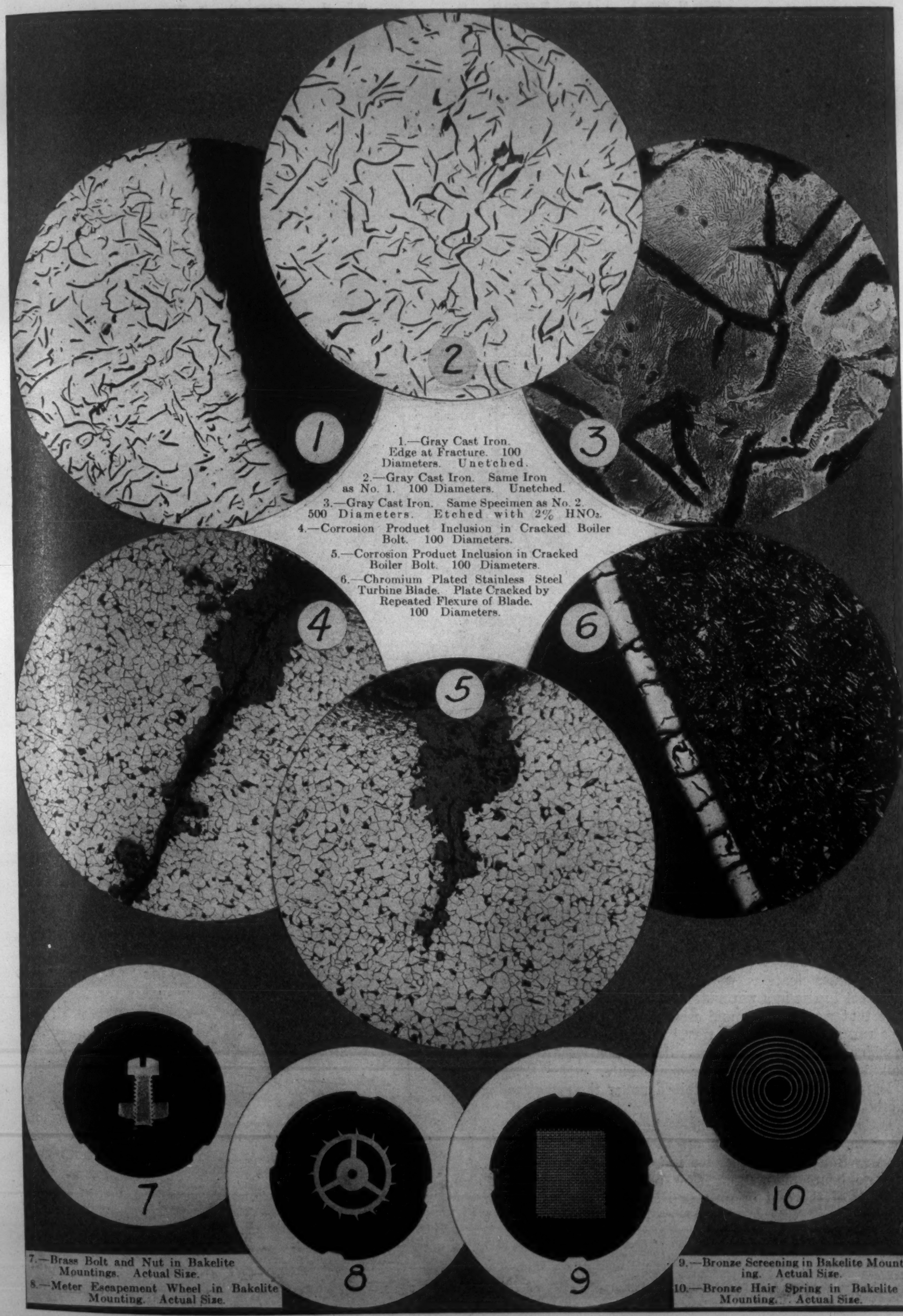












1.—Gray Cast Iron. Edge at Fracture. 100 Diameters. Unetched.

2.—Gray Cast Iron. Same Iron as No. 1. 100 Diameters. Unetched.

3.—Gray Cast Iron. Same Specimen as No. 2. 500 Diameters. Etched with 2% HNO_3.

4.—Corrosion Product Inclusion in Cracked Boiler Bolt. 100 Diameters.

5.—Corrosion Product Inclusion in Cracked Boiler Bolt. 100 Diameters.

6.—Chromium Plated Stainless Steel Turbine Blade. Plate Cracked by Repeated Flexure of Blade. 100 Diameters.

7.—Brass Bolt and Nut in Bakelite Mountings. Actual Size.

8.—Meter Escapement Wheel in Bakelite Mounting. Actual Size.

9.—Bronze Screening in Bakelite Mounting. Actual Size.

10.—Bronze Hair Spring in Bakelite Mounting. Actual Size.

BISMUTH ALLOYS

By J. G. Thompson

An Extended Abstract by H. W. Gillett

The Bureau of Standards, in coöperation with the Cerro de Pasco Copper Company, has been studying the properties of bismuth. Thompson[1] has collected previous data, and presented much new information.

Bismuth being associated with lead in many lead ores, it would be possible to produce lead-bismuth alloys directly. Hence, the Pb–Bi system was the starting point for this series of investigations. The tensile properties of this system up to 50% Bi are shown in Fig. 1. On account of the plastic nature of such alloys, the speed of testing must be strictly controlled if comparable results are to be obtained.

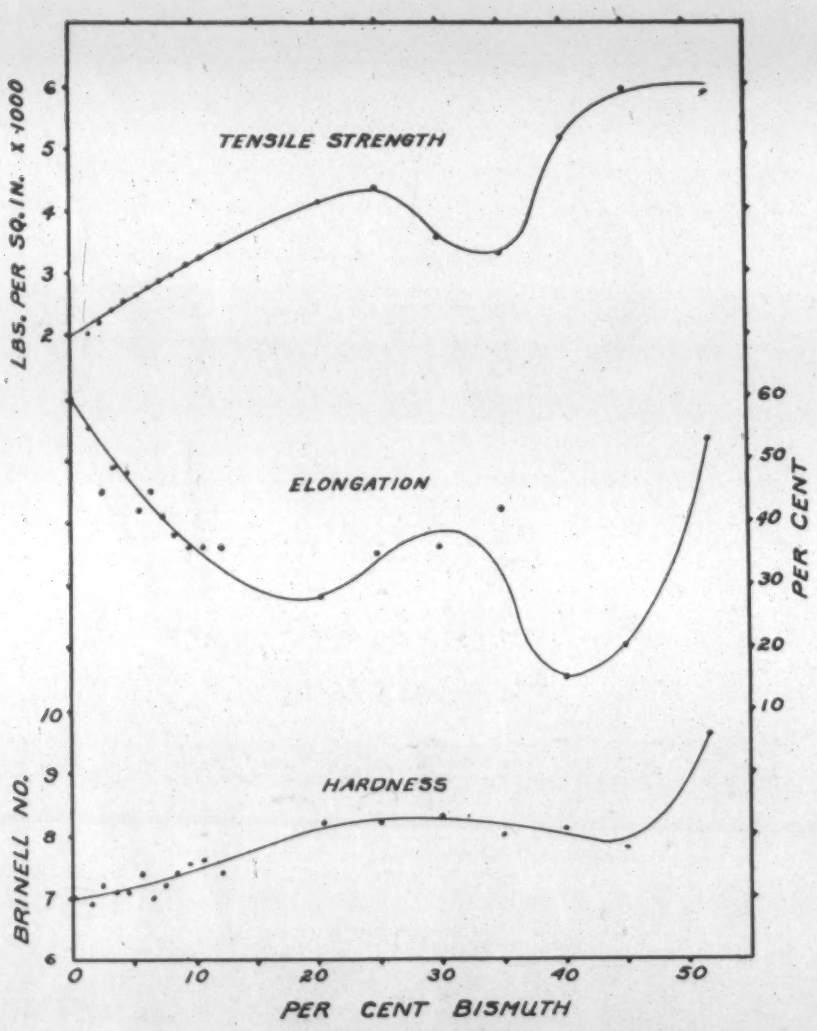


Fig. 1.—Mechanical Properties of Lead-Bismuth Alloys

The determinations were made on 0.505 in. diameter bars cast to size in a warm steel mold at the lowest temperature that would give sound castings. The testing machine was run at $^1/_2$ in./minute travel of the head of the testing machine. Brinell hardness was determined with a 10 mm. ball, 100 kg. load, applied for one minute.

Data for Pb-Sn alloys, obtained under the same testing methods, are shown in Fig. 2.

Precipitation hardening effects in the cast Pb-Bi alloys were studied and the results are shown in Fig. 3. Quenching was from 120° C. into ice water, annealing at 120° C. for two hours followed by slow cooling.

Aging of the cast or quenched specimens were at room temperature. Notable effects from heat-treatment are met only with a Bi content over 35%. Worked alloys might show it at lower percentages.

Preliminary experiments on the replacement of some of the tin in soft solders by a small amount of bismuth were promising, as the melting point was lowered, and the sur-

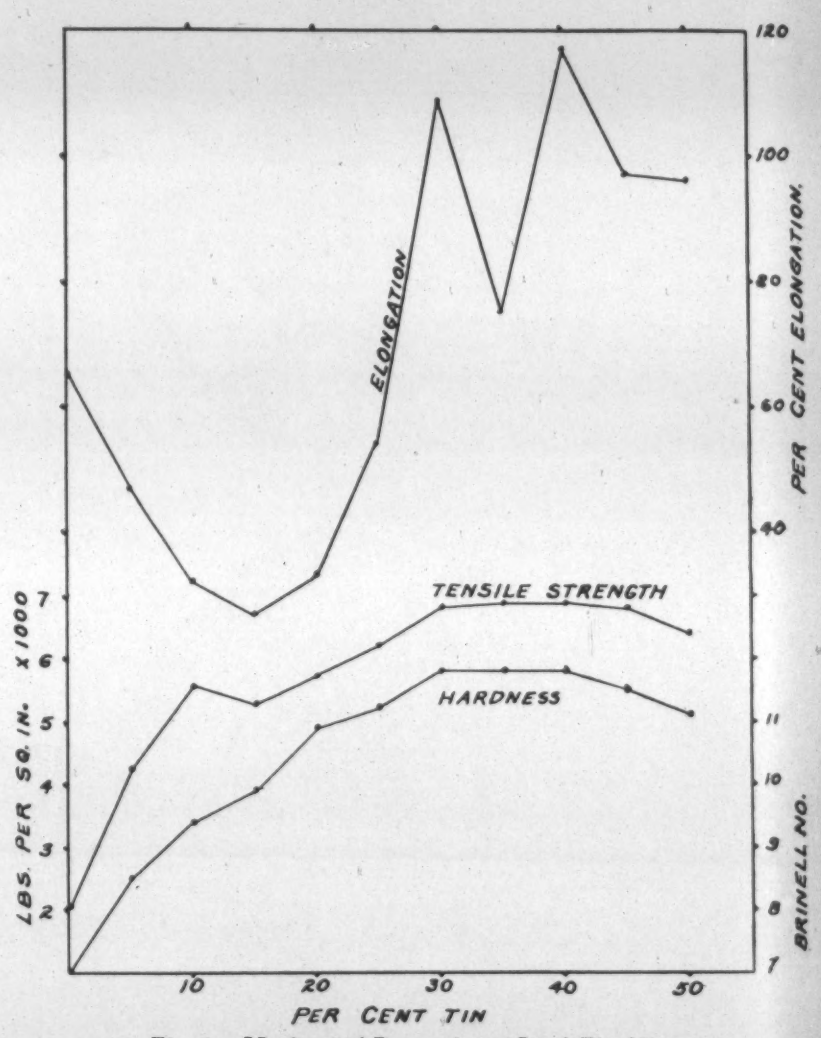


Fig. 2.—Mechanical Properties of Lead-Tin Alloys

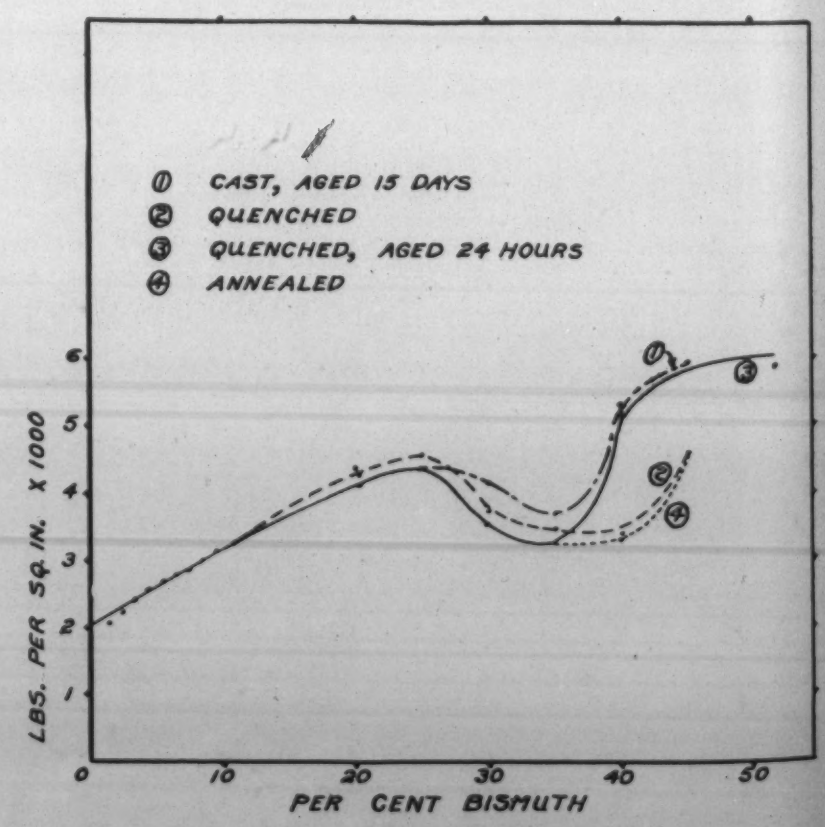


Fig. 3.—Effect of Heat Treatment and Aging on the Mechanical Properties of Lead-Bismuth Alloys

[1] Thompson, J. G., Bismuth. *Bureau of Standards Circular* No. 382, 1930. Reviewed in *Metals & Alloys*, May 1930, page 530.
Lead Bismuth, Lead-Tin, Type Metal and Fusible Alloys. *Bureau of Standards Journal of Research*, November 1930, pages 1085–1107.
The Use of Bismuth in Fusible Alloys. Bibliography of 43 references *Bureau of Standards Circular* 388.

Table 1—Mechanical Properties of Type Metals

No.	Description	Composition Pb %	Sb %	Sn %	As %	Cu %	Tensile Strength lbs./in.²	Elongation in 2 Inches %	Brinell Hardness Number
				MONOTYPES					
194		76.4	15.3	8.3	low	low	12,030—	4.0	22.0
195		70.3	19.5	10.2	low	low	11,425	2.5	25.4
196		70.3	19.4	10.3	low	low	11,500	2.0	25.7
205		75.7	16.8	7.3		0.2	11,700	3.0	25
				STEREOTYPES					
204							12,380	5.0	21
207		80.3	13	6.5		0.18	12,050	4.0	22
185		80.6	14	5.3	0.06	0.01	11,190	1.0	21.5
189	185 + 5% Bi						10,350	6.0	19.0
188	Synthetic 185 + 5% Bi	(No As or Cu)					11,470	3.5	21.6
				LINOTYPES					
203							11,950	9.0	20.5
206		84	11.5	4.4		0.08	11,700	9.0	21.0
186		85	11.4	3.5	0.06	0.05	10,840	15.5	18.4
190	186 + 5% Bi						10,400	9.2	15.8
				FOUNDRY TYPE					
197		61	25	12		2.0	7,390	2.5	35
				SYNTHETIC TYPE METALS (10% Sb)					
				Bi					
198		90	10				9,080	26	17
199		85	10		5		8,220	22	15.8
200		82.5	10	2.5	5		9,270	15	16.5
201		80	10	5	5		10,150	11.0	17.8
				SYNTHETIC TYPE METALS (15% Sb)					
191		85	15				9,300	11.7	17
192		80	15		5		8,000	9.0	14.8
193		77.5	15	2.5	5		8,370	5.2	15.8
208		70	15		15		5,810	2.3	14.2
				ADDITION OF BISMUTH TO STEREOTYPE NO. 207					
207		80.3	13	6.5		0.18	12,050	4.0	22
209	207 + 1% Bi						11,150	4.0	21
210	207 + 2% Bi						11,200	8.5	21
211	207 + 3% Bi						10,800	5.5	21.5
212	207 + 4% Bi						10,600	5.5	20
213	207 + 5% Bi						10,300	4.5	19.4

face tension reduced. The solders wet copper and brass well and compare favorably in mechanical properties and cost with the Pb-Sn solders.

In connection with type metals, the question of volume change in passing from liquid to solid was considered. The change for Pb-Bi and Pb-Sb alloys is shown in Fig. 4. This does not take account of the coefficient of contraction in the solid state, between the freezing point and room temperature. The prevalent idea that type metals in general, and Pb-Bi alloys in particular expand on solidification is true only for alloys with over 50% Bi or 70% Sb. Ordinary type metals contract slightly on solidification. The sharpness of the castings from them is due primarily to the low surface tension of the alloys in the liquid state.

Table 1 and Fig. 5 show the tensile strength, elongation and hardness (determined on cast specimens by the procedure mentioned above) for type metals with and without bismuth.

Fig. 6 shows stress deformation curves for these alloys

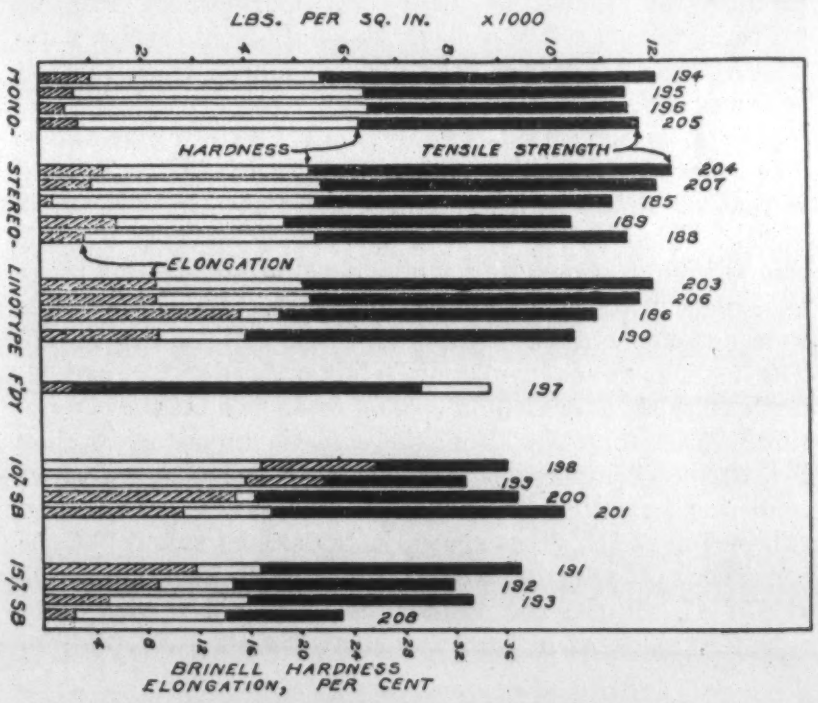


Fig. 5.—Mechanical Properties of Type Metals

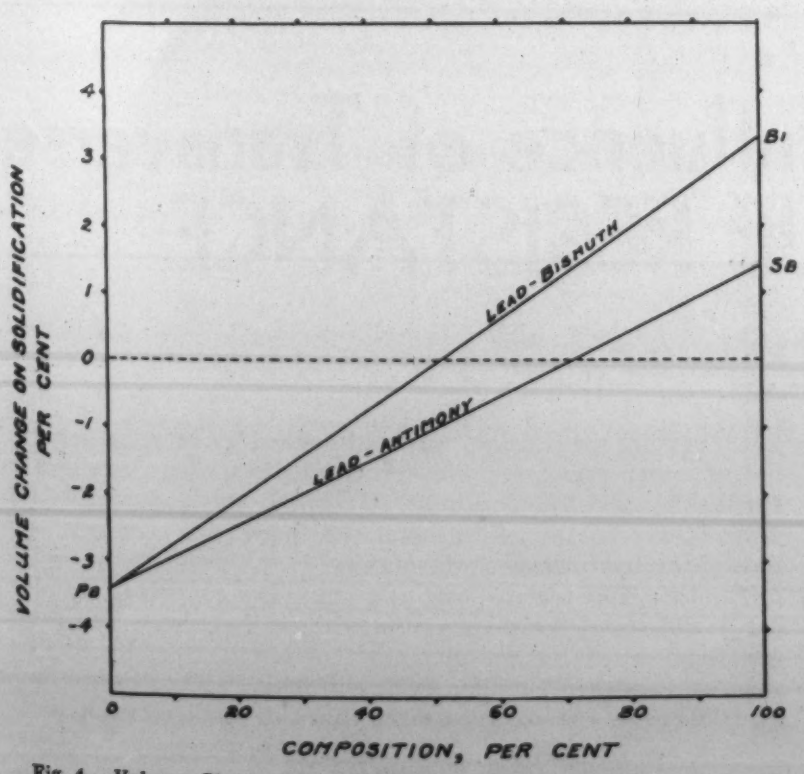


Fig. 4.—Volume Changes on Solidification of Lead-Antimony and Lead-Bismuth Alloys

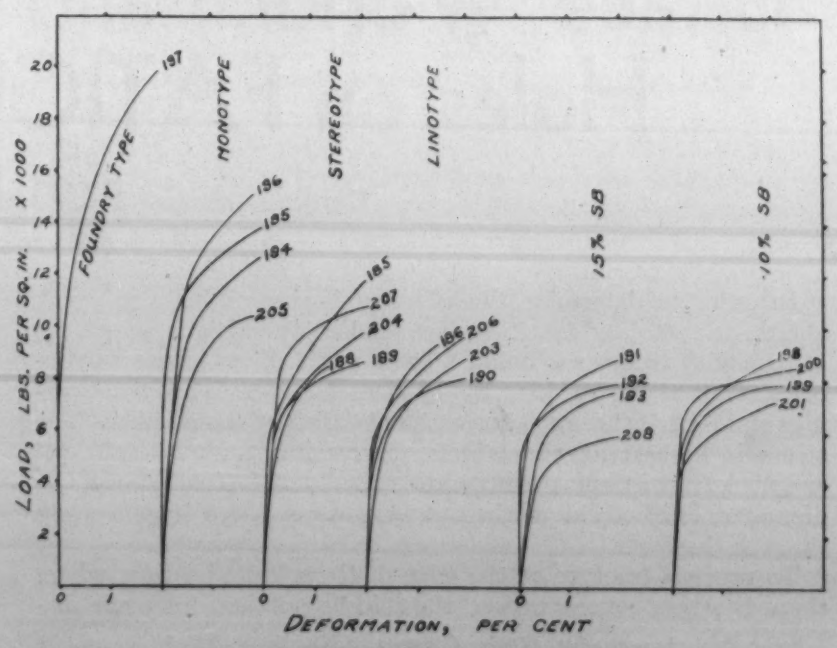


Fig. 6.—Compression Tests on Type Metals

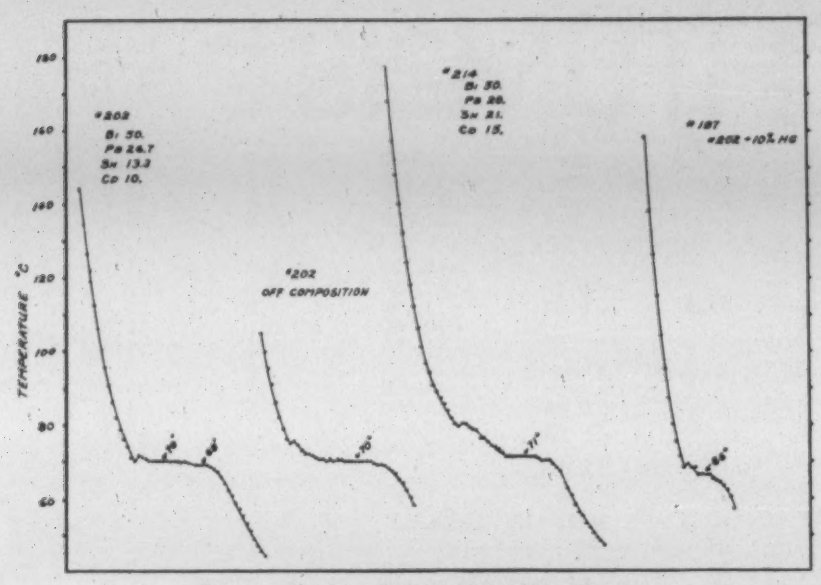


Fig. 7.—Cooling Curves of Fusible Alloys

in compression. Castings were made $1^1/_8$" diameter, and turned to specimen 1" long, 1" diameter. A specimen was loaded for one minute, removed and the permanent set measured. Another fresh specimen was then loaded to a higher stress in the same fashion, and so on till the curve, up to 2% deformation, was established. While bismuth slightly decreases the strength and hardness of the type metal alloys, it does lower the freezing point, and appears to help in producing sharp castings. As the "casting properties" of type metals are their most important attributes, enough promise was shown to justify the Government Printing Office in making a trial of bismuth additions in regular work. The results of this trial are to be announced when the test is completed.

One of the important uses for bismuth is in fusible alloys. The lowest melting alloy obtainable with Bi, Pb, Sn and Cd is that of 50, $26^2/_3$, $13^1/_3$ and 10% respectively of these metals. That this is at least a close approach to eutectic composition, is shown by the absence of a solidification range as is seen by the cooling curves of Fig. 7. No solid crystals were detected until the temperature had dropped to 71° C. The melt became completely solid at 70–69° C., and no further arrests appeared on cooling to 45° C. If the composition varies somewhat from the eutectic values, as in alloy No. 202 "off composition" in which only the cadmium varies from the eutectic proportions, most of the solidification still occurs at 70° C. as shown in the second curve, but the curve shows the appearance of a solidification range beginning at 75° C. If the composition deviates still further from eutectic values, as in the third curve for alloy No. 214, Bi 50; Pb 20; Sn 21; Cd 15; crystals will begin to appear at about 90° C., solidification begins at 80° C., at 75° C. it is no longer possible to stir the semi-solid mass, and solidification is complete at 70° C. The fourth curve of the series shows the effect of the addition of 10% by weight, of mercury on the melting point of the eutectic alloy No. 202. This amount of mercury lowers the solidification point to about 66° C. It will require, therefore, appreciably more than 10% mercury to lower the melting point to 60° C.

Some of the mechanical properties of Parravano's eutectic alloy (Wood's metal) and the effect on these properties of the addition of 10% mercury to the alloy are shown in Table 2.

Table 2—Mechanical Properties of Very Fusible Alloys

	Tensile Strength lbs./in.²	Hardness Brinell No.	Elongation in 2 in. %	Solidification Point ° C.
No. 202—Bi 50, Pb 26.7, Sn 13.3, Cd 10	5,990	9.2	140.0	70
No. 187—No. 202 + 10% Hg	5,970	8.9	89.0	66
No. 187—Aged 6 weeks at room temperature	6,000	10.0	42.5	

These mechanical properties were determined on cast test bars, 0.505 in. in diameter, and each figure given in the table is the average of three determinations. The data show that the tensile strength of the eutectic alloy is not appreciably affected by the addition of 10% mercury, although the Brinell hardness, % elongation and solidification point all are lowered. One of the test bars of No. 202 alloy exhibited remarkable elongation. With the testing machine set for 0.5 in./minute free travel, the test bar stretched without breaking until the limit of travel of the machine was reached. The original gage length was stretched out to more than 6 in. Such elongation is unusual in an alloy which approaches eutectic composition. This alloy apparently could be drawn to wire without difficulty. The data also indicate that the addition of mercury produces susceptibility to aging. Six weeks aging at room temperature did not affect the tensile strength of the alloy which contained mercury but increased the hardness somewhat and decidedly decreased the elongation. The freezing temperatures for fusible alloys containing Bi, Pb, Sn and Cd given in the literature are often decidedly in error. Figures are usually given for definite melting points, and are often below 70° C. Only the quaternary eutectic has a sharp freezing point, and there are no alloys of this series freezing below 70° C. The usual addition to produce alloys of still lower melting point is mercury. Mercury-containing alloys are looked upon with suspicion by some makers of fire alarm systems, who doubt their ability to function as desired over a period of years.

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Surface Working and Influence of Transverse Holes on FATIGUE RESISTANCE

By H. Doring*

Extended Abstract by H. W. Gillett

In order to determine the effect of boring oil-holes in crank shafts, the Wöhler Institute has studied the fatigue properties of bars with transverse holes. Their method was to use a cylindrical shaft about 30" long by 1" diameter, rotating in ball bearings and loaded through another ball bearing at the middle. The stress is highest at the middle, decreasing toward each end and the stress at any point can be calculated. Holes about $^1/_4$" diameter finished in various ways, were bored transversely through the shaft.

To prevent fracture at the edge of the middle bearing, where there is stress concentration, the middle portion, for some distance beyond the bearing, was cold-worked by rotating between rollers under pressure. This procedure has been described in English by von Heydekampf.[1] It raised the endurance limit some 10 percent on all the materials used save cast iron, and thus prevented fracture at the middle.

The procedure was to start at a stress low enough so that the bar would stand 2 million cycles without fracture. The stress was then raised by an increment of about 1500 lbs./in.² on steel, and another 2 million cycle run made, and so on till fracture did ensue. It was recognized that this involved strengthen-

* *Veroffenlichungen des Wöhler-Instituts.* No. 5 (1930) 50 pages, 11 tables, 30 figures. Published by N.E.M.-Verlag Berlin. Price 5 RM.

[1] G. S. von Heydekampf. Cold Rolling Raises Fatigue or Endurance Limit. *Iron Age*, Vol. 126 (1930) pages 775–777.
Should Steel Machinery Parts be Cold-Rolled? *Iron Age*, Vol. 126 (1930) pages 928–929.

ing by understressing, and 2 million cycles is not enough on non-ferrous materials to show whether fracture will finally ensue or not. Comparisons are made on the basis of a stress that, in virgin material, will allow a life of 2 million cycles, so the endurance limits taken as the bases of comparison are high in the case of the non-ferrous metals.

The stress at the point of fracture was figured from the moment-diagram, according to its distance from the middle, and the stress applied at the middle. If fracture occurred at the hole, that gave an exactly calculable nominal stress figure, but of course, this figure takes no account of the actual local stress. If fracture occurred in the solid specimen between the hole and the middle, it could only be calculated that the specimen would withstand a higher stress at the location of the hole than was there applied.

Various extrapolations are required, and there are admitted inaccuracies in the method. The percentage reduction in fatigue strength is figured first on the basis of a solid bar, and second, on the basis of the reduced section. With the bar and hole used, the hole was so large that (without calculating any enhanced local stress) the calculated extreme fiber stress was around twice that upon a solid bar. On the first basis, the holes cut the fatigue resistance by 55 to 80 percent, and on the second basis, allowing for the reduced section, by 25 to 65 percent. A total of 80 bars of 9 different materials were tested.

Several ways of making the hole were tried. The normal way was to bore through, and take off the burr at the exit. Others were polishing the bore of the hole with fine abrasive to round off the edge, pressing a ball or a mandrel through, countersinking, pressing in a ball or a cone. Oddly enough, rounding the edge by polishing did not seem to help, and all the other schemes tended to produce a burr at or near the end of the bore, and the author concludes that a burr sticking up is just as bad as a reëntrant notch. The normal way was thought the best.

On account of the number of variables studied, and the number of bars that did not break at the hole, and thus only gave an upper limit of stress, no very exact tabulation can be made to show the variation in notch effect from the hole. Lumping all the variously-finished holes together, we may tabulate Döring's results roughly as follows.

Compositions

Marine bronze—57.5% Cu, 0.8% Ni, 0.15% Sn, 0.15% Al, 0.50% Pb, balance Zn.
Lautal—4% Cu, 2% Si, balance commercial Al.
Carbon steel—0.35% C (D. I. N. Specification 1611).
NiCr—0.25–0.40% C, 3½% Ni, ¾% Cr (D. I. N. Specification 1662).
Ni Cr W Mo—0.40% C, 1.15% Cr, 2.5% Ni, 0.9% W, 0.25% Mo.
Cr V—0.50% C, 1.05% Cr, 0.17% V
Ni Cr Mo—0.16% C, 1.90% Cr, 4.90% Ni, 0.70% Mo.
Condition and heat-treatment not stated. All are presumably wrought materials.

Material	Static Properties		Endurance Limit	Percentage Reduction in Endurance Limit (No allowance for effect of strengthening by understressing)	
	Tensile Strength lbs./in.²	Elong., %	(For 2 million cycles only), lbs./in.²	Compared With Solid Shaft, %	On Basis of Reduced Cross-Section, %
Marine Bronze	83,500	15	25,000	60 to 70	20 to 50
Electrolytic Cu	48,000	11	18,000	60 to 70	30 to 45
Lautal	56,500	26	21,000	65 to 75	35 to 55
Lanz Pearlitic Cast Iron	36,000	<1	20,000	55 to 65	25 to 40
Carbon Steel	109,000	18½	47,500	65 to 75	30 to 45
Ni Cr Steel	130,500	18	70,500	70 to 75	50 to 55
Ni Cr W Mo Steel	175,000	11½	78,000	60 to 80	30 to 55
Cr V Steel	178,000	8½	87,000	65 to 80	35 to 65
Ni Cr Mo Steel	190,500	11	77,000	60 to 65	30 to 40

The Lanz cast iron appears to be, as one would expect from other recent work on cast iron, somewhat less affected by the hole than the other materials. The interesting thing is that the hard 190,000 lb. tensile Ni Cr Mo steel does not show greater percentage of injury by the hole than does copper. The lower ductility of the Cr V steel at the heat-treatment used might be considered to be reflected in the high maximum values for percentage reduction of endurance limit as compared with the other hard but more ductile steels, but against that it shows a much higher endurance ratio in the usual test, according to Döring's figures.

One might have hoped that such a test might bring out the susceptibility to notch propagation practical men associate with very hard steels as compared with soft ones, but it does not seem to.

Döring includes some side comments on the effect of surface notches produced in various ways, and discusses the fact that some specimens broke in the cold worked section, the nucleus of the fatigue failure lying at inclusions below the surface instead of on the surface. The fractures, which are shown and discussed by von Heydekampf, are like those in transverse fissured rails or in ball-bearings where fracture often starts beneath the surface.

While students of the fatigue of metals will be disappointed at the scatter of Döring's results, and may be doubtful of the precision of the method, the article is of very great interest, and it may well spur others to follow analogous lines of attack.

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Friction and Wear Tests on Solid Dry Bodies*

By E. Zimmerman

Extended Abstract by H. W. Gillett

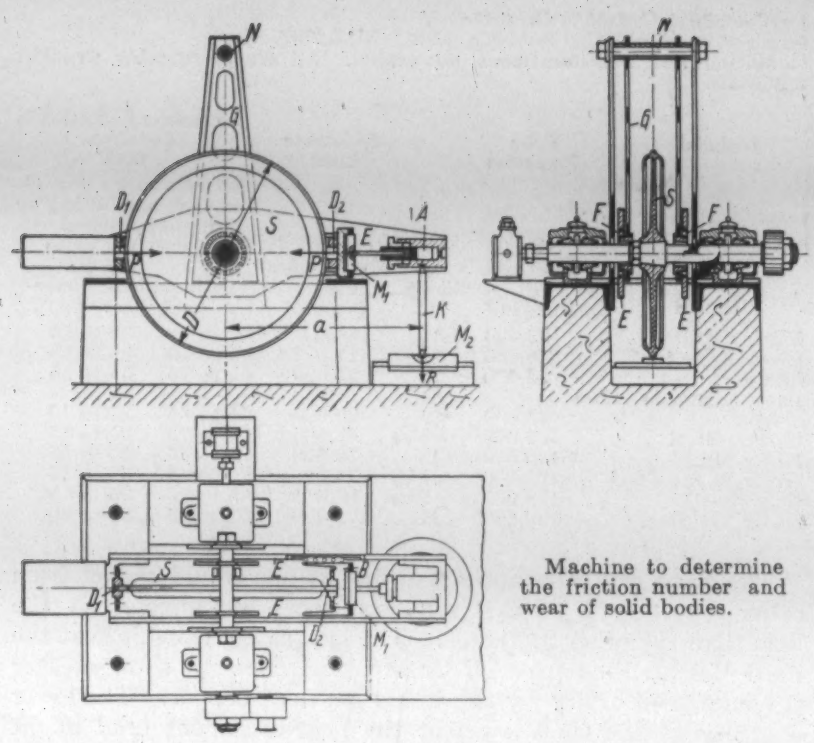
Experiments were made with a rotating disk of forged steel of 88,000 lbs./in.² tensile strength, 14.3% elongation. Two samples of the material to be tested were pressed against the periphery of the disk on opposite sides. The specimens were held in a floating frame, suspended like a pendulum, and the pressure of the specimens against the disk could be changed at will. Four pressures, ranging from 1½ to 12 kg./cm.² (20–170 lbs./in.²) and 4 or 5 disk-speeds ranging from 5 to 20 (sometimes 50) m./sec. (16–63 ft./sec.) were used. The energy in kwh. that would be required to remove a cc. of the material, or the number of hours running required to remove a cc. at a given pressure, was taken as the measure of wear. The volume was calculated from the weight loss and the specific gravity. The pendulum rigging of the supporting frame made possible its utilization as a dynamometer for the measurement of the coefficient of friction. The apparatus is shown in the diagram. The coefficient is dependent on the speed, the pressure and the temperature, but temperature measurements at the rubbing surface were not attempted in the study of metallic materials.

At the start of each new test the disk was polished with No. 0 emery paper, except in the tests on cast iron. Several non-metallic materials for brake-linings were studied, and a series of alloys. The observations are very sketchily reported, it being stated that the original data may be consulted at Aachen.

The only data given on the coefficient of friction of the cast irons studied are on a pearlitic gray cast iron of 170 Brinell, the results on other cast irons being said to be about the same.

The coefficient decreased with pressure and with speed. At 1½ kg./cm.² (20 lbs./in.²) the coefficient was about 0.42 at 10 m./sec. (32 ft./sec.), dropping to about 0.28 at 50 m./sec. (157 ft./sec.), while at 6 kg./cm.² (85 lbs./in.²), it was around 0.32 and 0.18 at these speeds. The decrease is ascribed to the collection of graphite particles on the contact surfaces. The periphery of the disk became coated with an adherent film which was left on in each run in which

* *Doctor's Dissertation, Technische Hochschule Aachen*, June 1929. Mimeographed, 24 pages, 15 figures, 51 references.



Machine to determine the friction number and wear of solid bodies.

tests were made at steps of increasing speed. A fresh disk would show a lower coefficient, the curve obtained with a series of fresh disks lying parallel to the one obtained with the filmed disk. The disk did not become badly attacked up to pressures of 10 or 12 kg./cm.² (142 or 170 lbs./in.²). However, the ferritic cast irons scored the disk deeply in 5 or 10 minutes at pressures as low as 6 kg./cm.² (85 lbs./in.²).

The plots of volume removed per hour are slightly curved. The loss-rates at 4, 8 and 12 kg./cm.² (57, 114 and 170 lbs./in.²), all observed at a speed of 10 m./sec. (32 ft./sec.), are given below as read from the curves for cast iron and bronzes. The analysis of the irons is not stated.

Table I. Cast Irons and Bronzes

	Brinell	Drilling Depth*	Description	cc. Removed per Hr. at Pressures Shown in kg./cm.² 4	8	12
Cast Iron No. 5	170	8.0	Pearlitic—fine, phosphide eutectic present	0.15	0.60	1.10
Cast Iron No. 9	215	6.5	Pearlitic—fine, phosphide eutectic present	0.20	0.60	0.95
Cast Iron No. 10	221	6.7	Pearlitic—fine, phosphide eutectic present	0.30	0.85	1.70
Hard Iron No. 11	468	..	Outside white, inside shows graphite	0.20	0.50	1.00
White Pig Iron No. 15	436	..	Fine—cast in chill	0.15	0.40	0.70
White Pig Iron No. 17	436	..	Coarse, cast in hot sand	0.10	0.35	0.60
Cast Bronze D. I. N. No. 14 86% Cu 14% Sn	127**	3.0	....	1.20	2.60	Failed
Ackermann Leaded Bronze 22% Pb 5% Sn 3% Ni 1% Co 1% As 0.5% P Balance Cu	76**	24.4	Slowly solidified in the crucible	0.20	0.25	0.30

* Depth drilled in mm. in 100 revolutions of a 10 mm. drill at 450 R. P. M. under a pressure of 180 kg.
** 10 mm. ball—1000 kg. pressure.

A series of Cu-Zn alloys were studied, both cast and rolled material being used. All specimens lasted only a few minutes and it was concluded that the brasses are not fitted for use as brakes. Another series was then made up in which varying amounts of lead were added to a 63% Cu, 37% Zn brass. The lead-free alloy and those with 1 and 2% Pb showed high wear and tests could only be made up to 3 kg./cm.² (43 lbs./in.²). The more highly leaded alloys with 5, 10 and 20% Pb showed a coefficient of friction rising from about 0.1 at 2 kg./cm.² (28 lbs./in.²) for all three, to 0.5, 0.3 and 0.2, respectively, at 6 kg./cm.² (85 lbs./in.²). The wear rose, on all three alloys, to a maximum at 4 kg./cm.², the values in cc./hr. at that pressure being 11.0, 8.0 and 2.5 for the 5, 10 and 20% Pb alloys. Then the wear fell to 5.0, 6.5 and 2.2, respectively, at 6 kg./cm.² (85 lbs./in.²).

The 5% Pb alloy could not be carried beyond that pressure. The 10 and 20% Pb alloys at 12 kg./cm.² (170 lbs./in.²) showed wear of 5.0 and 1.6 cc./hr.

The 5, 10 and 20% Pb alloys had Brinell hardness (10 mm. ball, 1000 kg. load) of 52, 52 and 48, while the drill hardnesses (at 50 kg. load on the drill) were 13.0, 18.2 and 26.8.

Data on white metal bearing alloys follow:

The alloys were cast at 500° C. in a steel mold, except the last 3 (Nico I and II and R. E.) which were sand-cast. The Brinell figures were taken with a 10 mm. ball and 250 kg. load. The drill hardness was taken as before, but with only 20 kg. pressure on the drill. The compression tests are for a stress producing 8% compression on a 20 mm. (1.27″) diameter 20 mm. (1.27″) high specimen.

Table II. White Metals

D. I. N. No.	Composition Sn	Sb	Cu	Pb	Brinell	Drill Hardness mm.	Stress at 8% Compression kg./mm.²	lbs./in.²	Av. Coef. of Friction	Av. Wear Rate cc./hr. at 3 kg./cm.² Pressure 10 m./sec. Speed
80 F	80	10	10	..	37.4	9.4	1420	20200	0.28	0.15
80	80	12	6	2	35	12.2	1320	18800	0.28	0.20
70	70	13	5	12	32	15.0	1280	18200	0.23	0.24
50	50	14	3	33	34	30.0	1020	14500	0.08	0.78
42	42	14	3	41	26.5	19.6	1090	15500	0.18	1.30
20	20	14	2	64	28.3	19.6	1250	17800	0.17	1.18
10	10	15	1.5	73.5	36	19.6	1440	20500	0.23	0.36
Nico I*	..		..	..	36	18.4	1205	17100	0.43	0.09
Nico II**	..		..	..	29	18.4	1100	15600	0.37	0.03
R. E.	83.4	11	5.6	..	33.5	13.0	1330	12900	0.22	0.18

* Nico I. A Pb alloy high in Sb (up to 23%) with some As and P. Sn about 4 to 5% and with 2 to 3% Ni.
** Nico II. A Pb alloy with approximately 10% Sn, 10% Sb, nickel about 1%, small amounts of As and P.
Both alloys are said to contain the compound Ni_2Sb_3.

In this series of tests the loss of weight of the 2 specimens did not agree well, particles torn off from one specimen were carried over on the disk and taken up by the other. Average values for the 2 specimens are given in the table. The high losses of alloys Nos. 50, 42 and 20 were shown also at 6 kg./cm.² (85 lbs./in.²). Alloys Nos. 80 F, 80 and 70 stood up at a pressure of 12 kg./cm.² (170 lbs./in.²), with coefficients of friction between 0.2 and 0.3. Wear figures are not given for pressures higher than 3 kg./cm.² (42 lbs./in.²).

The author concludes that the coefficient of friction is not a distinct property of a material, but depends on condition of the surface, on pressure, speed and temperature. No universal relationship connecting these factors holds for all materials. There is no generally valid connection between coefficient of friction and compressive strength or Brinell or drill hardness. Neither is there any relation between these mechanical properties and the wear rate. As long as wear takes place by the tearing out of small particles, without lubrication, wear increases approximately as the square of the pressure. (However, the curves do not bear out this statement, the wear rates increase more rapidly than the pressure but not as the square of the pressure.)

Calendar of Meetings

American Society of Mechanical Engineers, Fourth National Fuels Meeting, Chicago, Ill., Feb. 10–24, 1931.
Fifth Midwest Power Engineering Conference.
Midwestern Power and Engineering Exposition.
Second Western Metal Congress, Auditorium, San Francisco, under auspices of American Society for Steel Treating, Feb. 16–20, 1931.
American Chemical Society, 81st Meeting, Indianapolis, Ind., Mar. 30–Apr. 3, 1931.
American Electrochemical Society, Hotel Tutwiler, Birmingham, Ala., Apr. 23–25, 1931.
Thirteenth Exposition of Chemical Industries, Grand Central Palace, New York, N. Y., week of May 4, 1931.
American Foundrymen's Association, Stevens Hotel, Chicago, Ill., week of May 4, 1931.